Nucleon spin and 3D structure studies at COMPASS

BAKUR PARSAMYAN

AANL, CERN, INFN section of Turin
on behalf of the COMPASS Collaboration

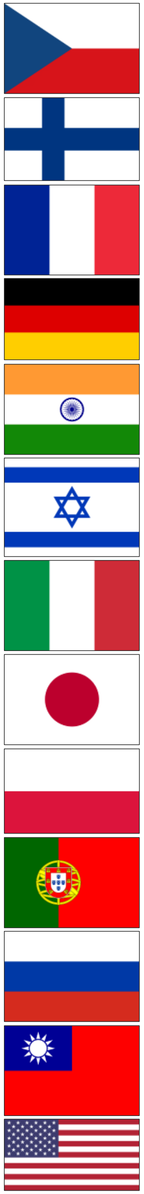
COMPASS
25 years
1997 - 2022

The XXXI International Workshop on
Deep Inelastic Scattering and Related Subjects
April 8 – 12, 2024, Maison MINATEC, Grenoble, France

DIS 2024

COMPASS collaboration

Common **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy



25 institutions from 13 countries
– nearly 200 physicists (in 2022)

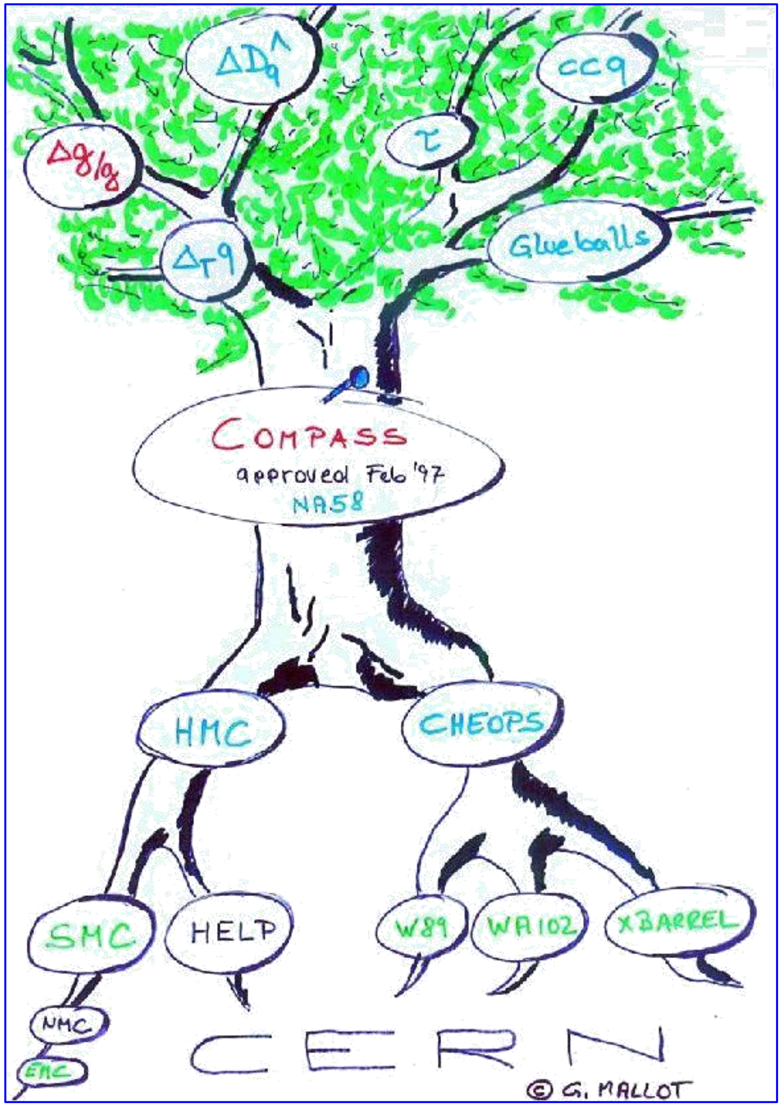
- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (25 years)**
- **Taking data since 2002 (20 years)**

International Workshop on Hadron Structure and Spectroscopy

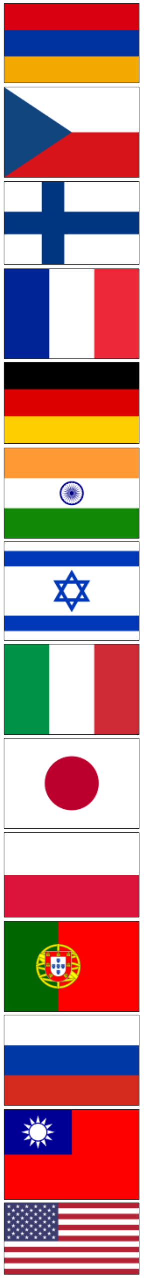
IWHSS-2022 workshop (anniversary edition)

CERN Globe, August 29-31, 2022

https://indico.cern.ch/e/IWHSS-2022



COMPASS collaboration



Common **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

28 institutions from 14 countries
– nearly 210 physicists (in 2023: start of the Analysis Phase)

3 new groups joined the COMPASS collaboration in 2023
UCon (US), AANL (Armenia), NCU (Taiwan)

- **CERN SPS north area**
- **Fixed target experiment**
- **Approved in 1997 (25 years)**
- **Taking data since 2002 (20 years)**

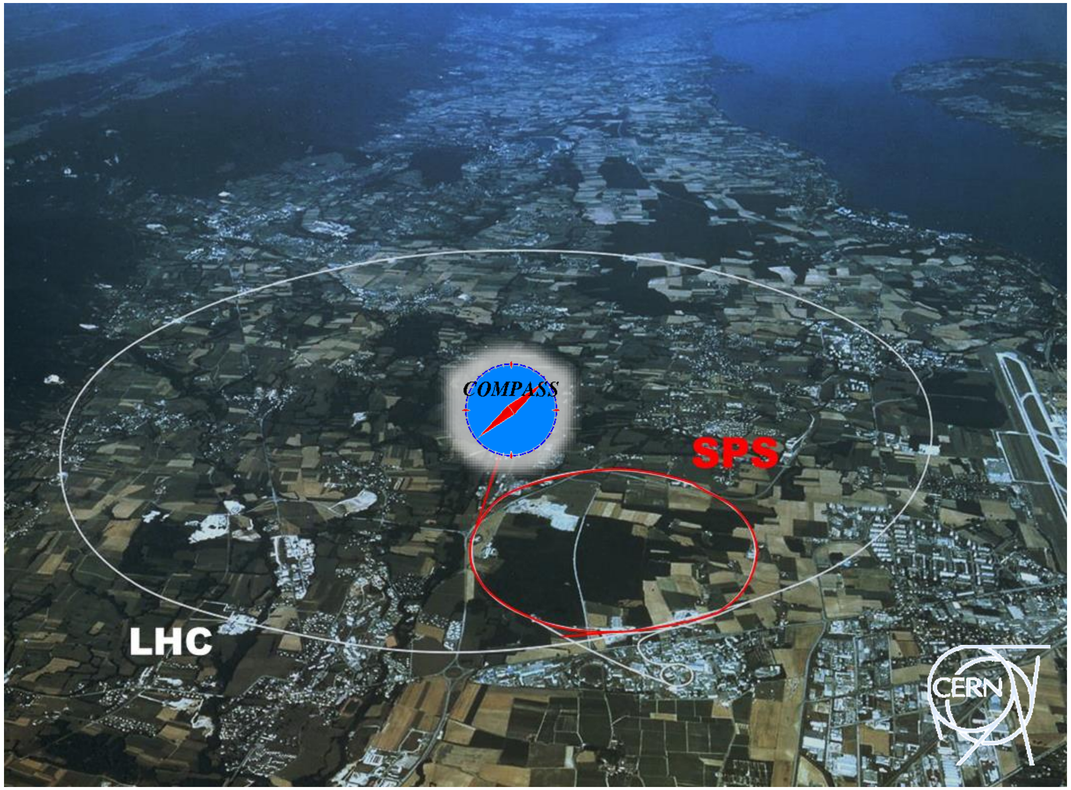
Wide physics program

COMPASS-I

- **Data taking 2002-2011**
- **Muon and hadron beams**
- **Nucleon spin structure**
- **Spectroscopy**

COMPASS-II

- **Data taking 2012-2022**
- **Primakoff**
- **DVCS (GPD+SIDIS)**
- **Polarized Drell-Yan**
- **Transverse deuteron SIDIS 2022**



COMPASS web page: http://wwwcompass.cern.ch

See talks by: S. Asatryan, V. Andrieux, V. Benesova, M. Niemiec, M. Peskova, A. Sandacz, M. Stolarski

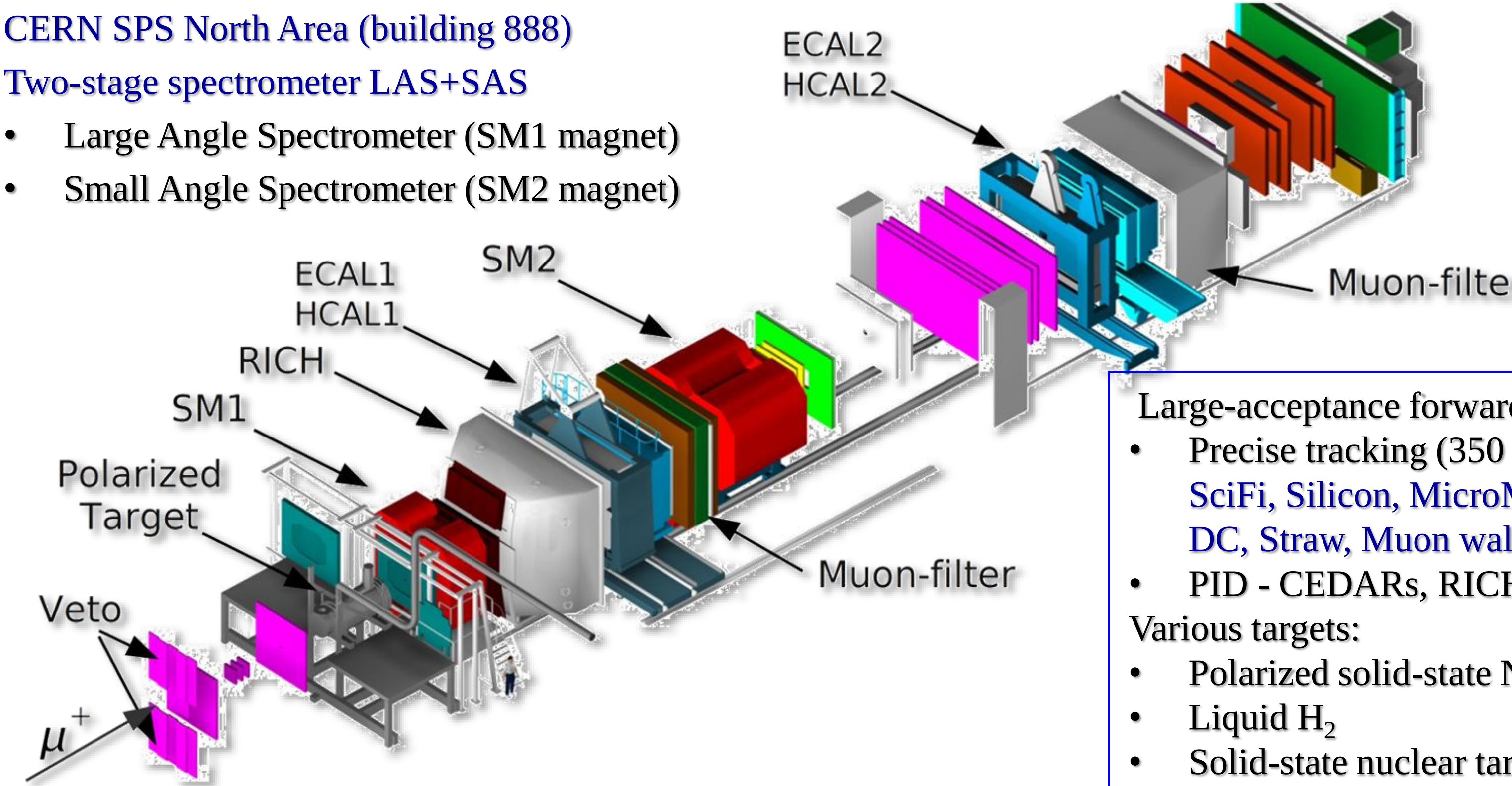
COMPASS experimental setup

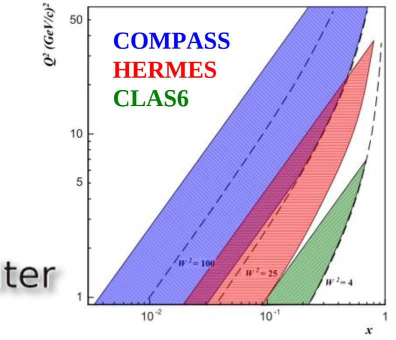
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)





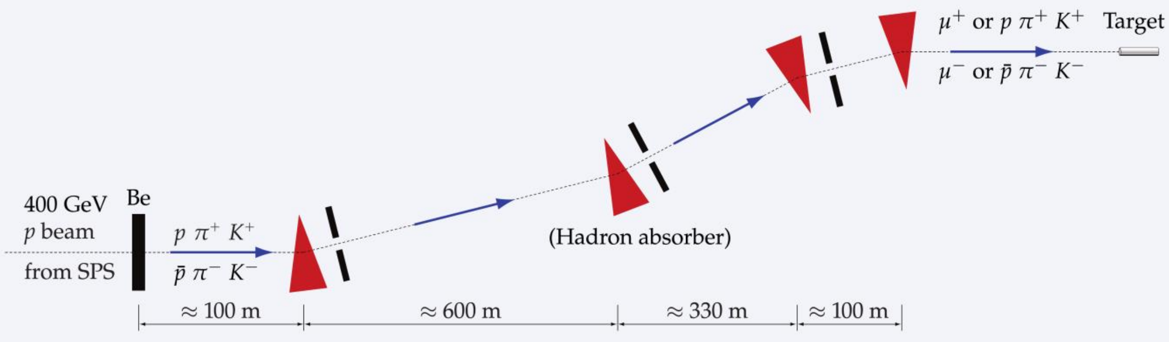
Large-acceptance forward spectrometer

- Precise tracking (350 planes)
  SciFi, Silicon, MicroMegas, GEM, MWPC, DC, Straw, Muon walls
- PID - CEDARs, RICH, calorimeters, MWs

Various targets:

- Polarized solid-state NH$_3$ or ^{6}LiD
- Liquid H$_2$
- Solid-state nuclear targets (e.g. Ni, W, Pb)

- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h$^-$ beam: 97% π^-, 2% K^-, 1% p
  - h$^+$ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized



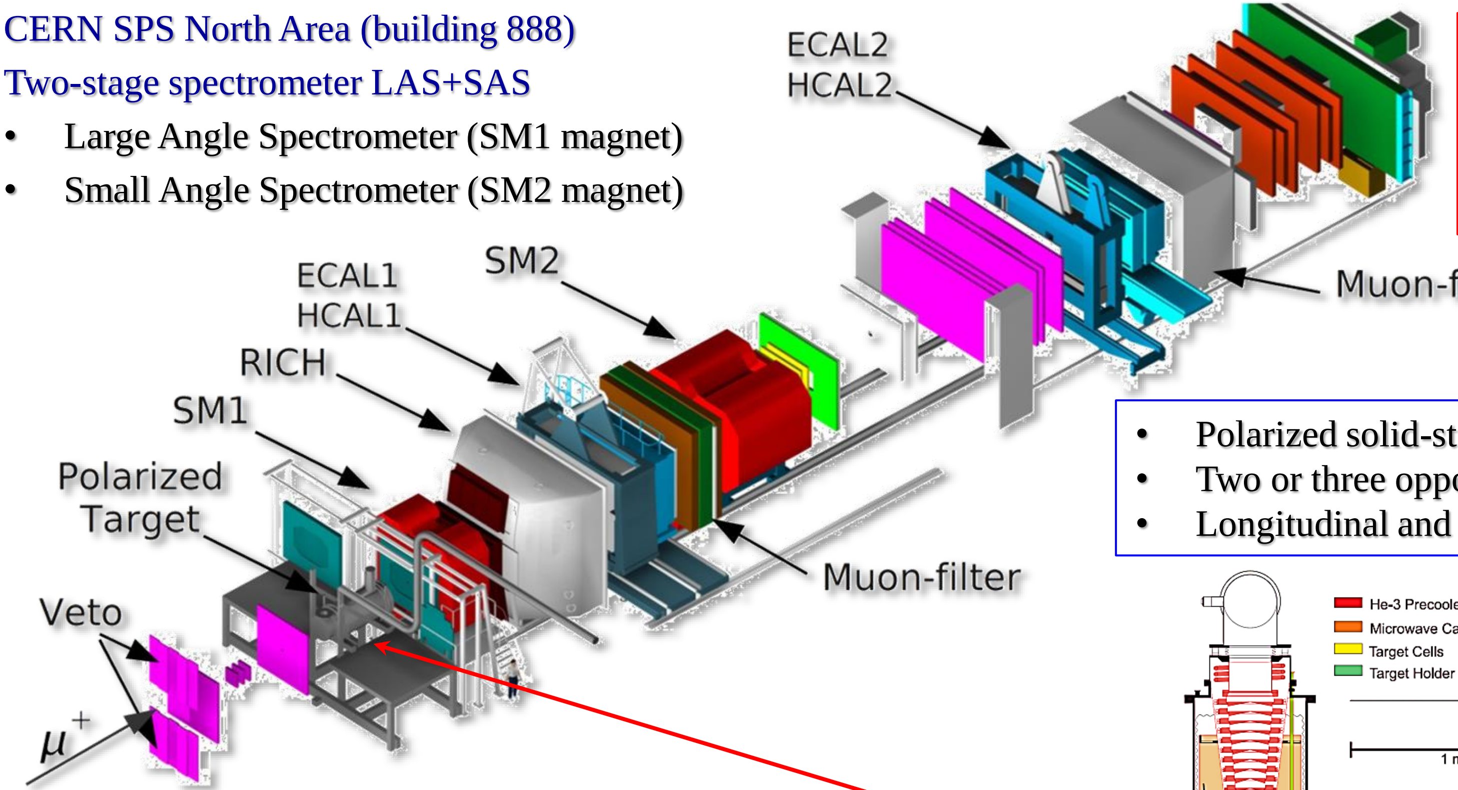
COMPASS experimental setup: Phase II (SIDIS programme)

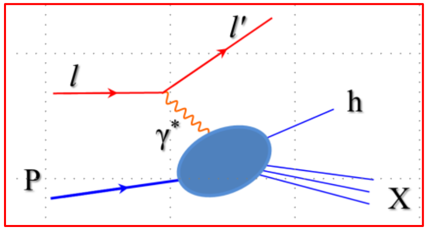
COmmon Muon Proton Apparatus for Structure and Spectroscopy

CERN SPS North Area (building 888)

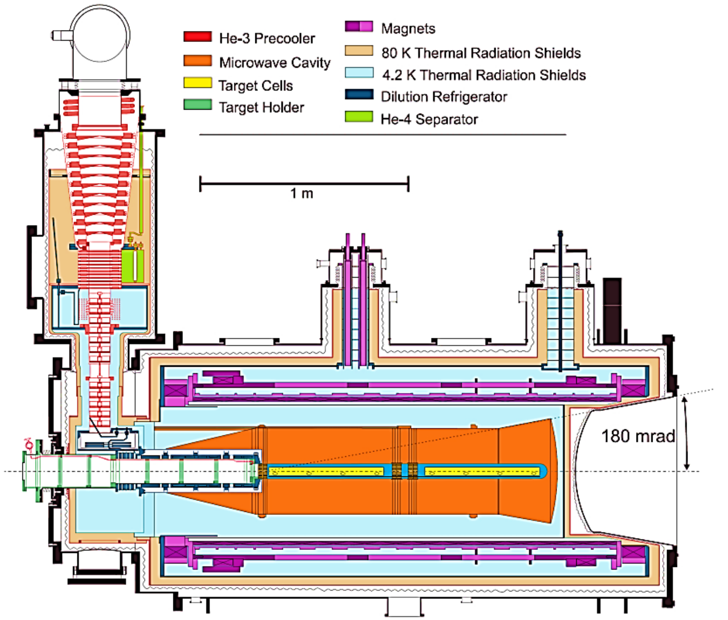
Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)





- Polarized solid-state NH_3 or ^{6}LiD
- Two or three oppositely polarized cells
- Longitudinal and transverse polarization



- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
  - h^+ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - μ^+ longitudinally polarized

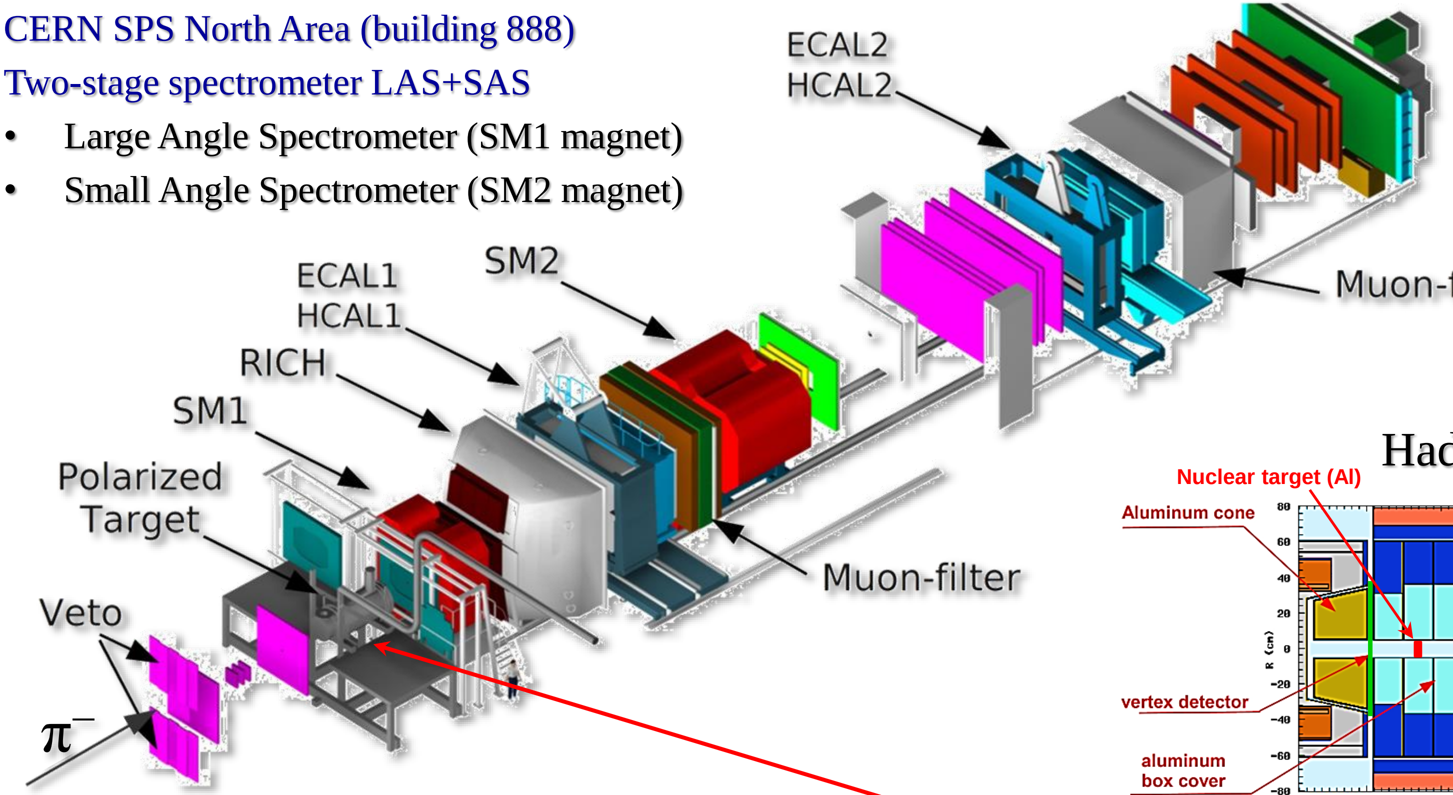
COMPASS experimental setup: Phase II (DY programme)

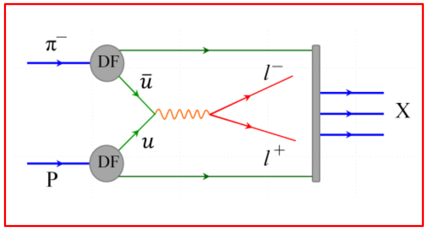
COmmon Muon Proton Apparatus for Structure and Spectroscopy

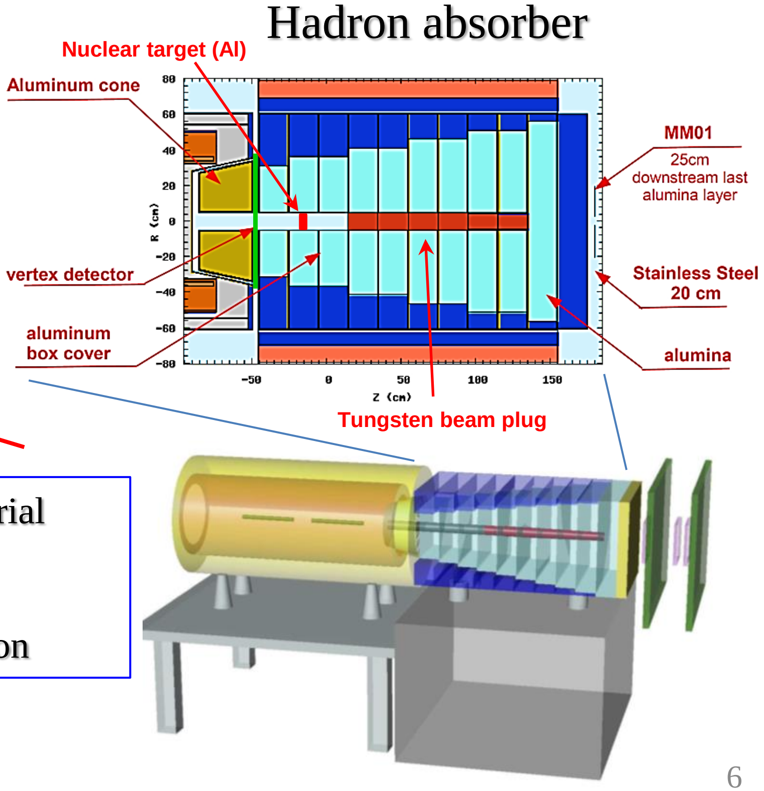
CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)







- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
  - h^+ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polarized

- Solid-state NH_3 material
- Two cells oppositely polarized
- Transverse polarization

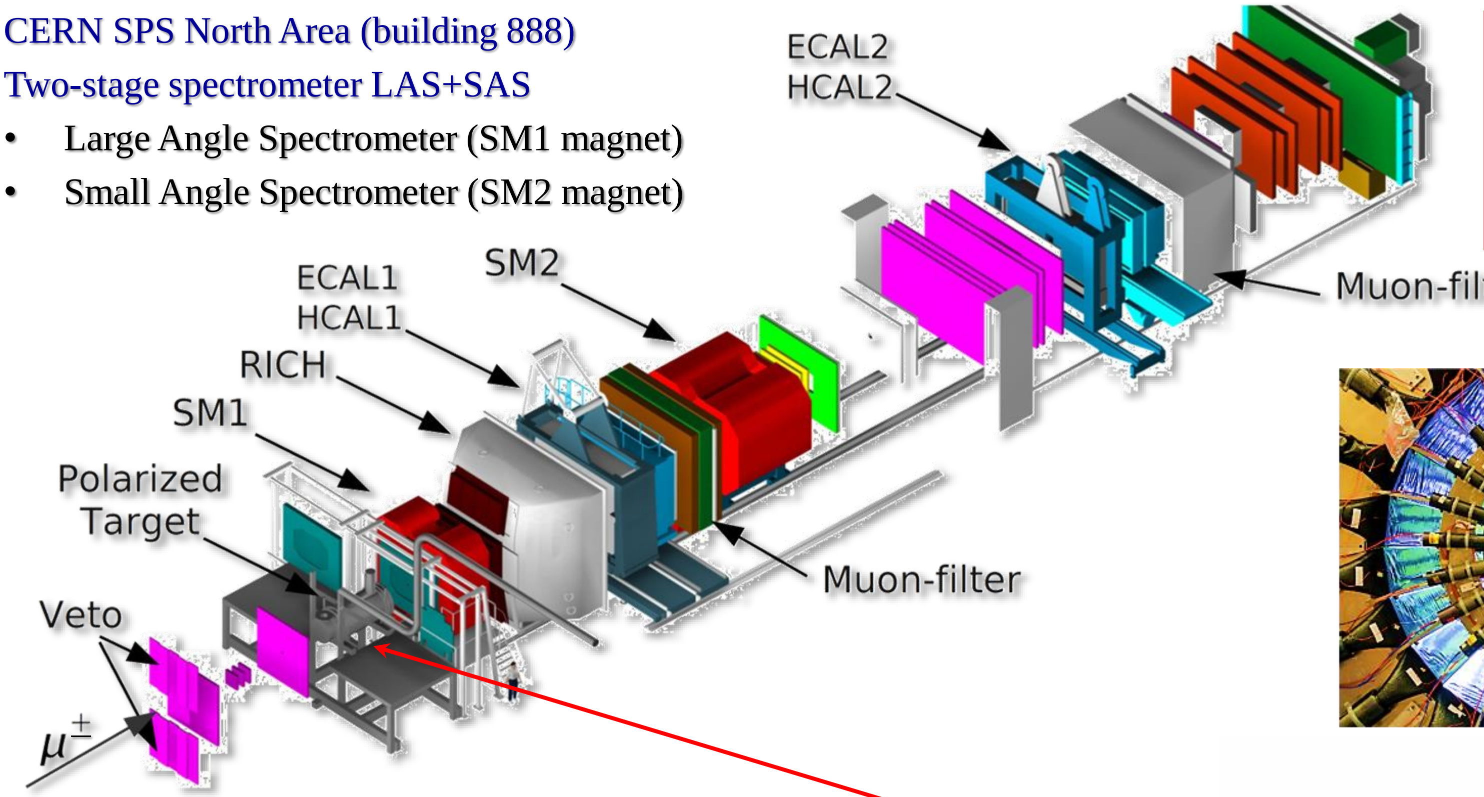
COMPASS experimental setup: Phase II (DVCS programme)

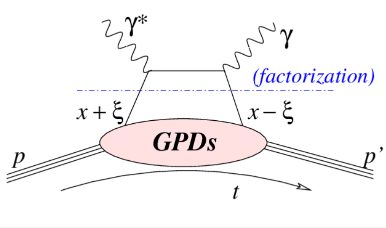
COmmon Muon Proton Apparatus for Structure and Spectroscopy

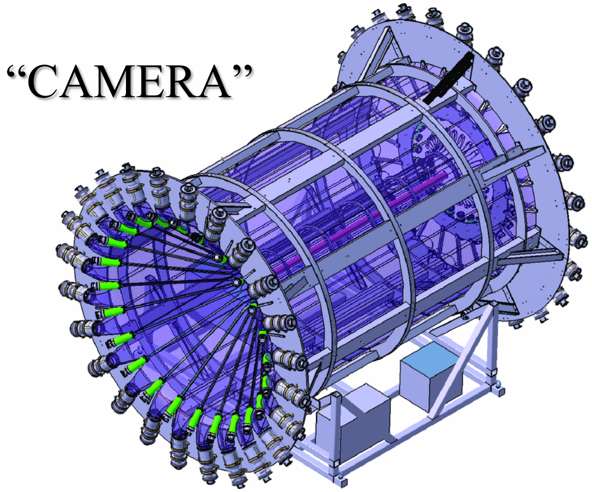
CERN SPS North Area (building 888)

Two-stage spectrometer LAS+SAS

- Large Angle Spectrometer (SM1 magnet)
- Small Angle Spectrometer (SM2 magnet)





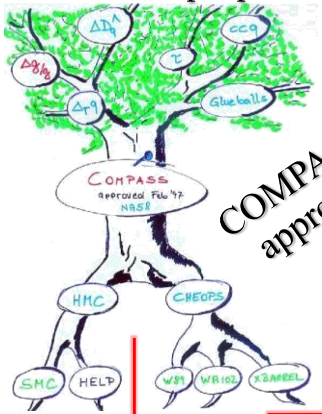


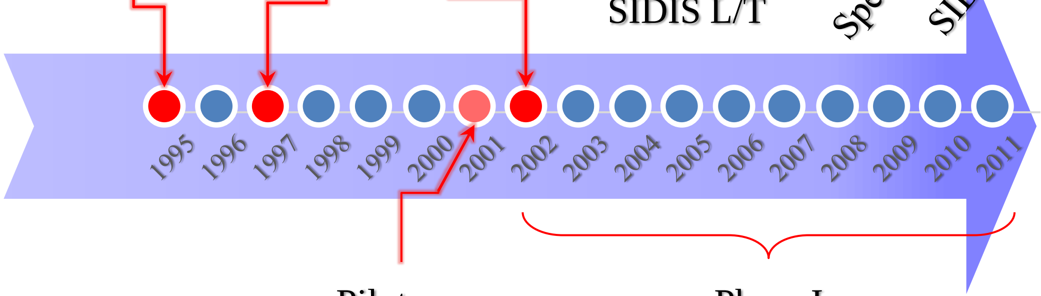
- Primary beam - 400 GeV p from SPS
  - impinging on Be production target (T6)
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
  - h^+ beam: 75% p, 24% π^+, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^{\pm}$ longitudinally polarized

- Unpolarized target
- Liquid H_2
- Recoil detector "CAMERA"

COMPASS timeline

COMPASS proposal





COMPASS approval

COMPASS 1st data taking

SIDIS L/T

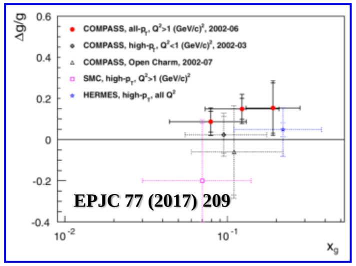
Spectroscopy

SIDIS L/T

Pilot run

Phase I

COMPASS timeline



EPJC 77 (2017) 209

NEWS

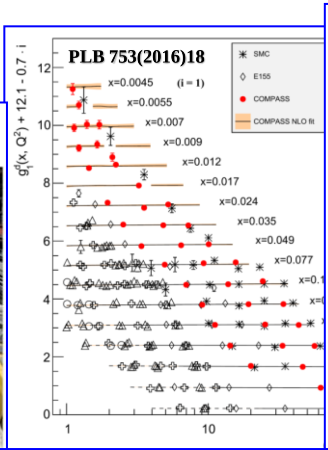
COMPASS measures the pion polarizability

23 February 2015

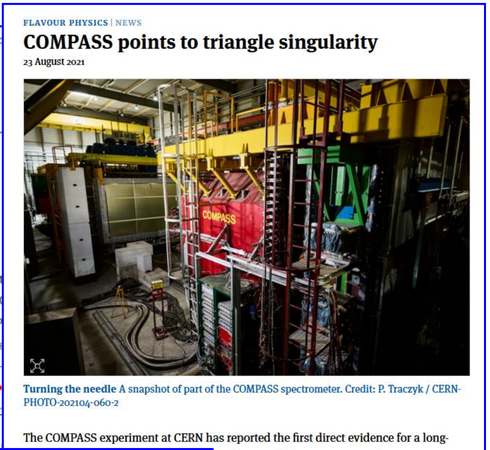
CERN experiment brings precision to a cornerstone of particle physics

11 FEBRUARY 2015

The COMPASS experiment in the North Area on the Prévessin site at CERN studies hadron structure both with pion beams and with muon beams – a powerful combination. Image credit: CERN-EX-1105182-01.



PLB 753(2016)18



FLAVOUR PHYSICS | NEWS

COMPASS points to triangle singularity

23 August 2021

Turning the needle A snapshot of part of the COMPASS spectrometer. Credit: P. Traczyk / CERN-PHOTO-202104-060-2

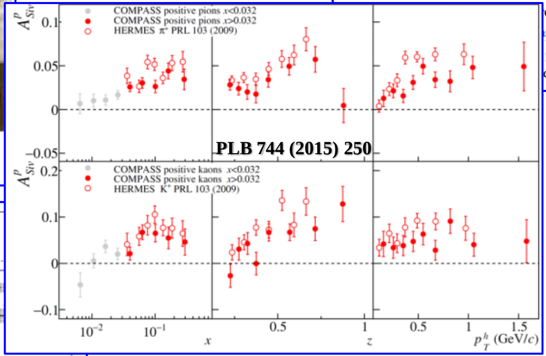
The COMPASS experiment at CERN has reported the first direct evidence for a long-

on decays which can masquerade as a resonance.

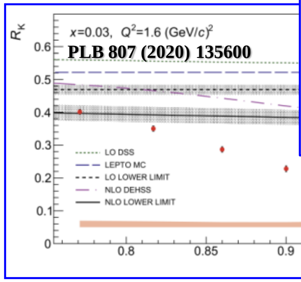
ast week in Physic

collaboration in

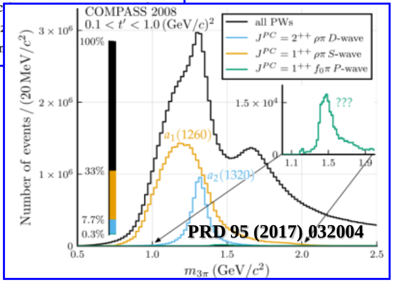
called triangle si



PLB 744 (2015) 250

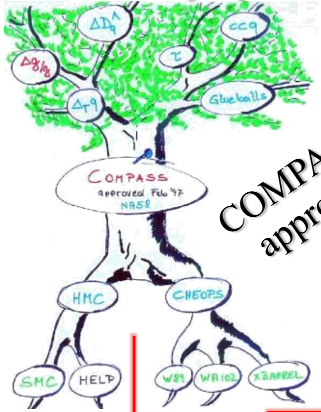


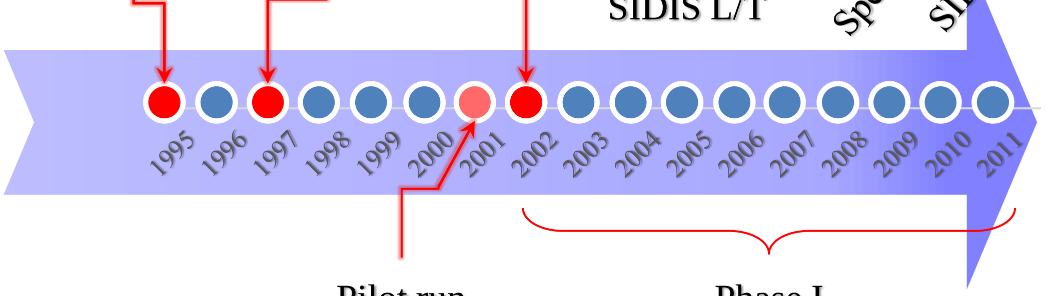
PLB 807 (2020) 135600



PRD 95 (2017) 032004

COMPASS proposal





COMPASS approval

COMPASS 1st data taking

SIDIS L/T

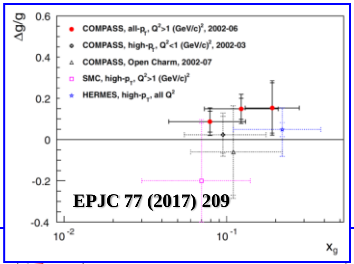
Spectroscopy

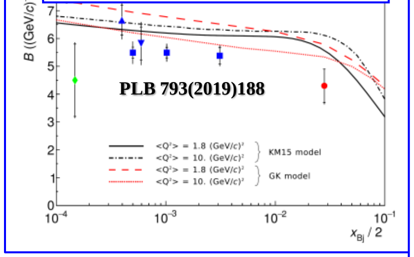
SIDIS L/T

Pilot run

Phase I

COMPASS Legacy






NEWS

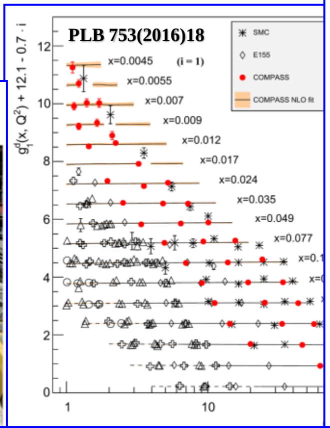
COMPASS measures the pion polarizability

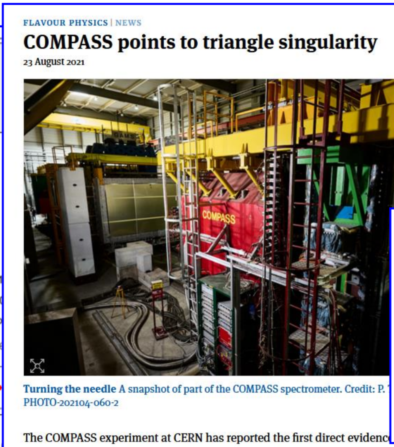
23 February 2015

CERN experiment brings precision to a cornerstone of particle physics

11 FEBRUARY 2015

The COMPASS experiment in the North Area on the Prévessin site at CERN studies hadron structure both with pion beams and with muon beams – a powerful combination. Image credit: CERN-EX-1105182-01.




FLAVOUR PHYSICS | NEWS

COMPASS points to triangle singularity

23 August 2021

CERN COURIER

Turning the needle A snapshot of part of the COMPASS spectrometer. Credit: P.

PHOTO-202104-060-2

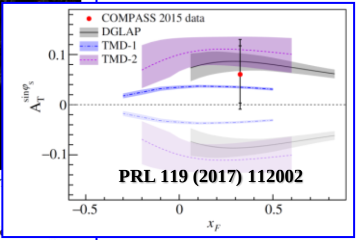
The COMPASS experiment at CERN has reported the first direct evidenc

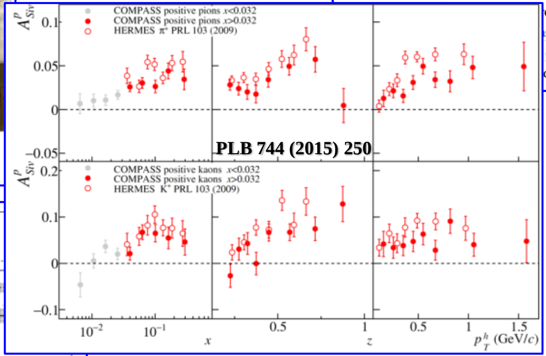
on decays which can masquerade as a resonance.

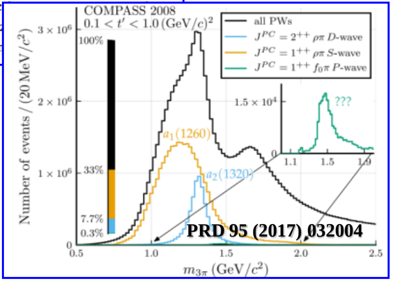
st week in Physic

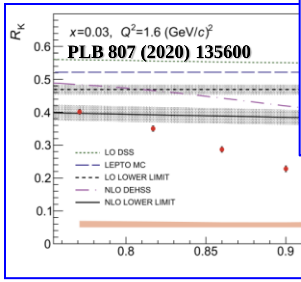
collaboration in

called triangle sin

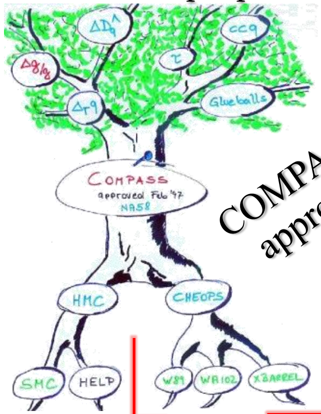


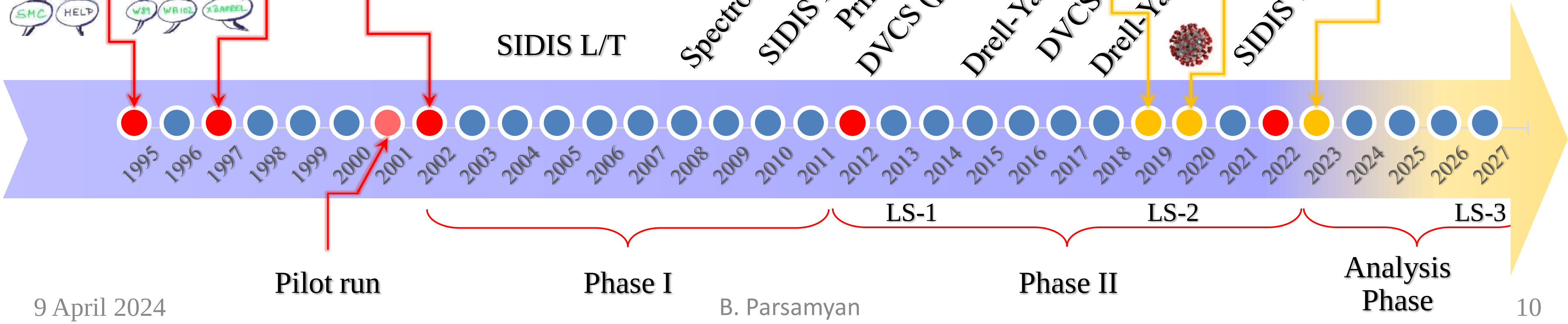






COMPASS proposal




COMPASS approval

COMPASS 1st data taking

SIDIS L/T

Spectroscopy

SIDIS L/T

Primakoff

DVCS (pilot)

Drell-Yan

DVCS

Drell-Yan

SIDIS T

COMPASS++/AMBER proposal

AMBER approval

AMBER 1st data taking

AMBER
Apparatus for Meson and Baryon Experimental Research

1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027

LS-1

LS-2

LS-3

Pilot run

Phase I

Phase II

Analysis Phase

The COMPASS Experiment at the CERN SPS

COMPASS 25 years 1997 - 2022

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer)

Nucleon structure

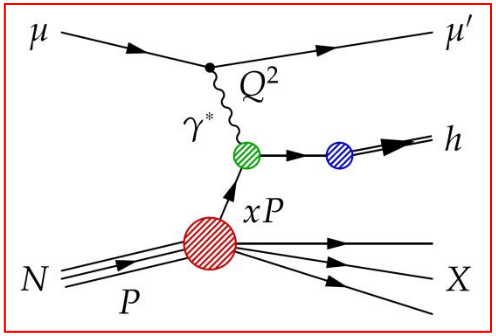
- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions

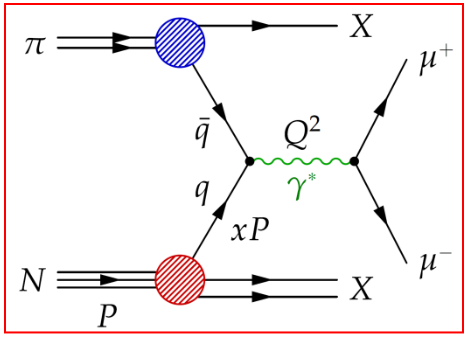
Hadron spectroscopy

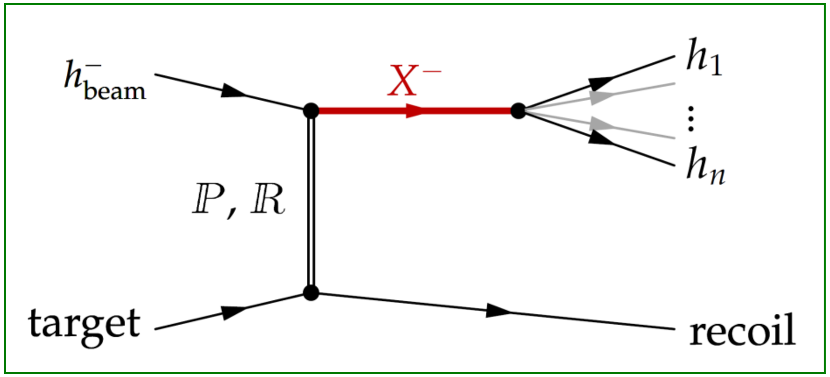
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

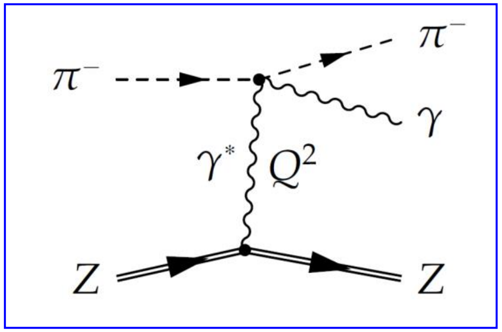
Chiral dynamics

- Test chiral perturbation theory in $\pi(K)\ \gamma$ reactions
- $\pi^{\pm}$ and $K^{\pm}$ polarizabilities
- Chiral anomaly $F_{3\pi}$









The COMPASS Experiment at the CERN SPS

Broad Physics Program to study Structure and Excitation Spectrum of Hadrons

Increasing resolution scale (momentum transfer)

Nucleon structure

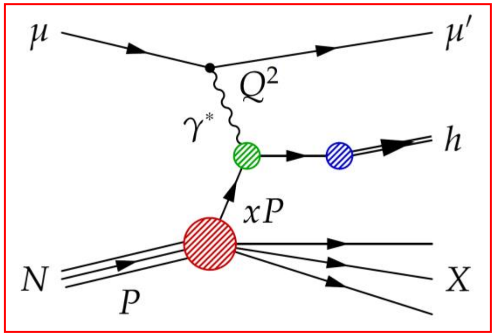
- Hard scattering of $\mu^{\pm}$ and π^{-} off (un)polarized P/D targets
- Study of nucleon spin structure
- Parton distribution functions and fragmentation functions

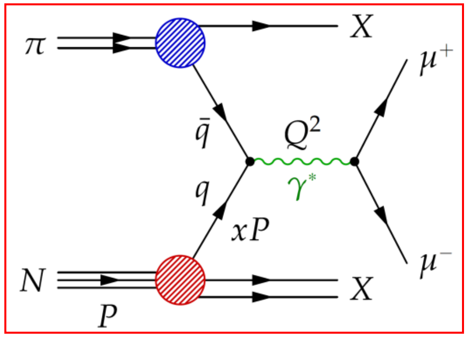
Hadron spectroscopy

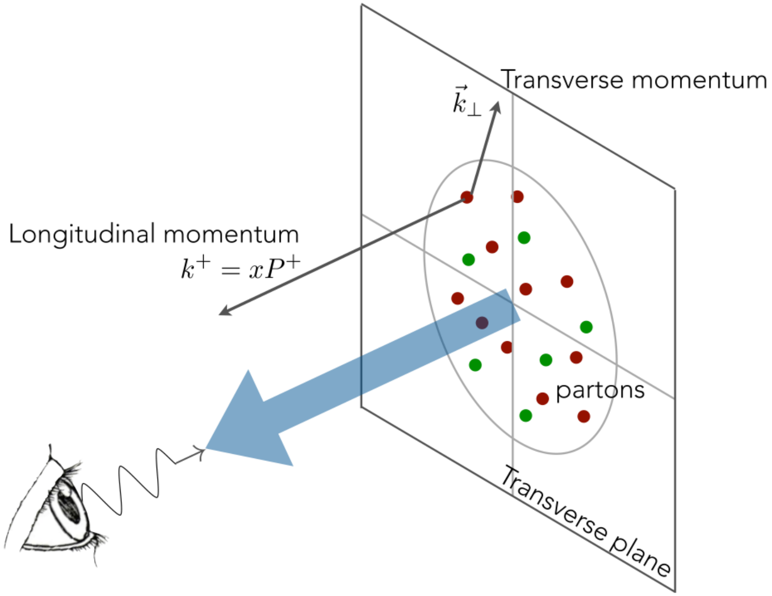
- Diffractive $\pi(K)$ dissociation reaction with proton target
- PWA technique employed
- High-precision measurement of light-meson excitation spectrum
- Search for exotic states

Chiral dynamics

- Test chiral perturbation theory in $\pi(K)$ γ reactions
- $\pi^{\pm}$ and $K^{\pm}$ polarizabilities
- Chiral anomaly $F_{3\pi}$



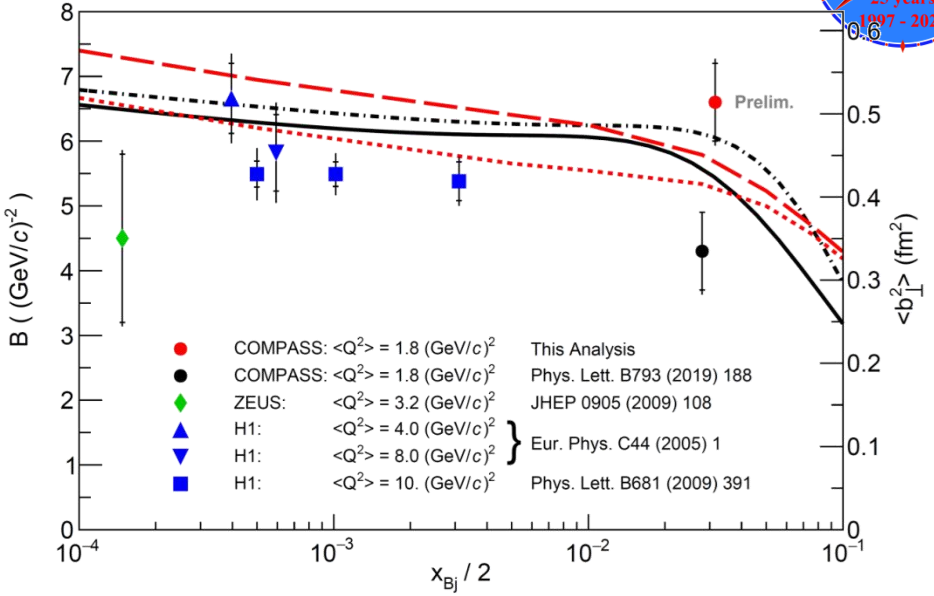


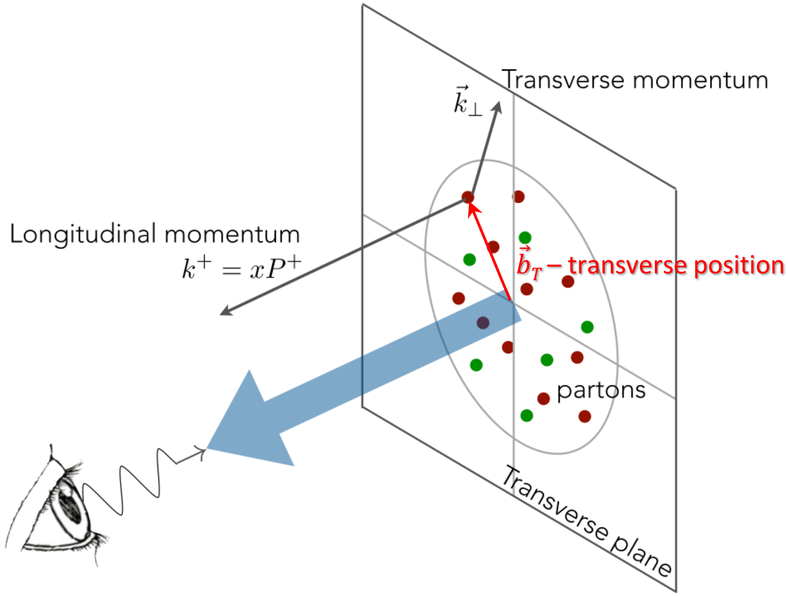


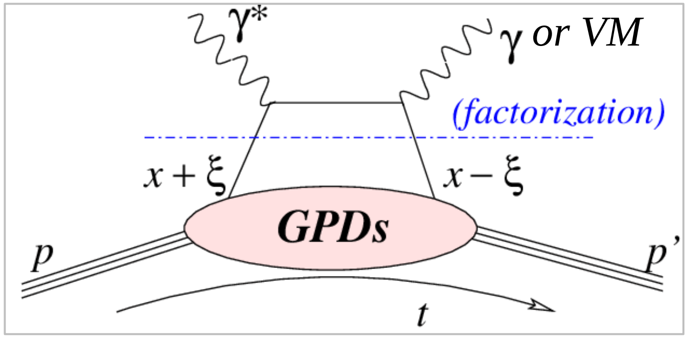
Nucleon 3D structure: GPDs

- Transverse position $\vec{b}_T$ of partons
  - Correlation between $\vec{b}_T$ and x
  - Complementary to TMD PDFs
- 8 generalized parton distribution functions (GPDs)
  - Contain information about parton orbital angular momentum
  - Mostly unknown
- COMPASS exclusive process measurements:
  - Deeply virtual Compton scattering (DVCS): $\mu + \mathrm{N} \rightarrow \mu + \gamma + \mathrm{N}$
  - Hard exclusive meson production (HEMP): $\mu + \mathrm{N} \rightarrow \mu + \mathrm{VM} + \mathrm{N}$ with VM = π^0, $\rho(770)$, $\omega(782)$,..

COMPASS 2016 data (2/3)



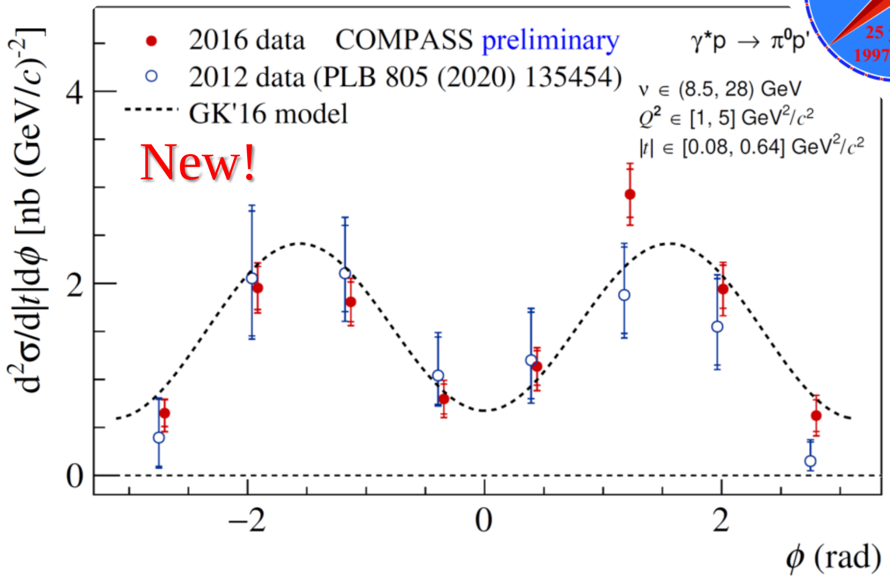


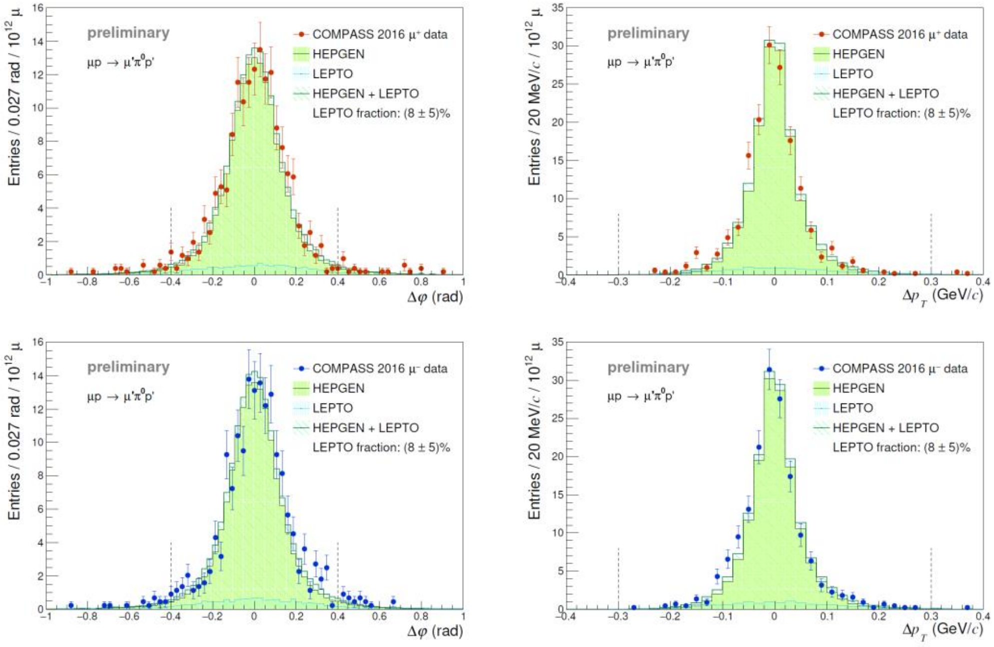


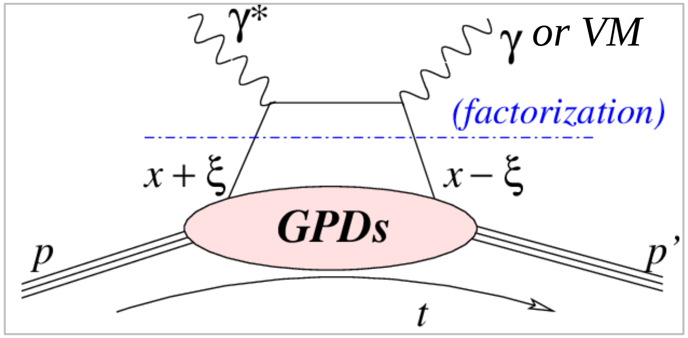
Nucleon 3D structure: GPDs

see M. Peskova's talk

- Transverse position $\vec{b}_T$ of partons
  - Correlation between $\vec{b}_T$ and x
  - Complementary to TMD PDFs
- 8 generalized parton distribution functions (GPDs)
  - Contain information about parton orbital angular momentum
  - Mostly unknown
- COMPASS exclusive process measurements:
  - Deeply virtual Compton scattering (DVCS): $\mu + \mathrm{N} \rightarrow \mu + \gamma + \mathrm{N}$
  - Hard exclusive meson production (HEMP): $\mu + \mathrm{N} \rightarrow \mu + \mathrm{VM} + \mathrm{N}$ with VM = π^0, $\rho(770)$, $\omega(782)$,..







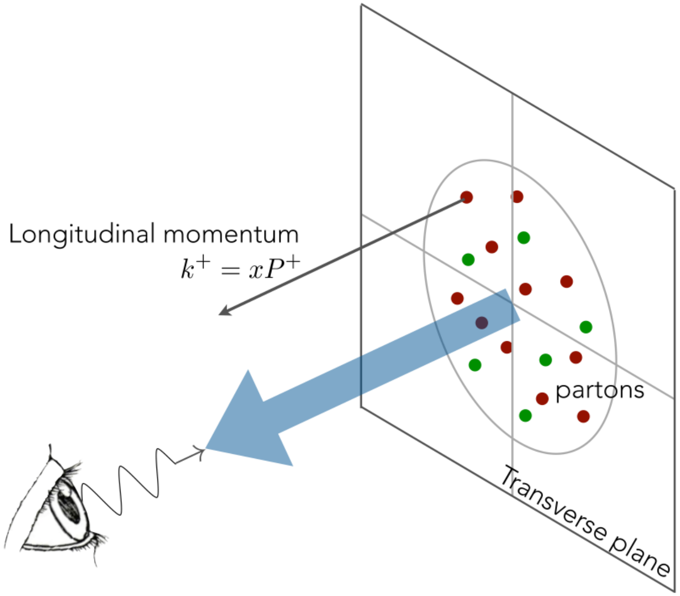
Nucleon spin structure: collinear approach ↔TMDs

		quark		
		U	**L**	**T**
nucleon	**U**	$f_1^q(x)$ **number density**		
	L		$g_1^q(x)$ helicity	
	T			$h_1^q(x)$ transversity

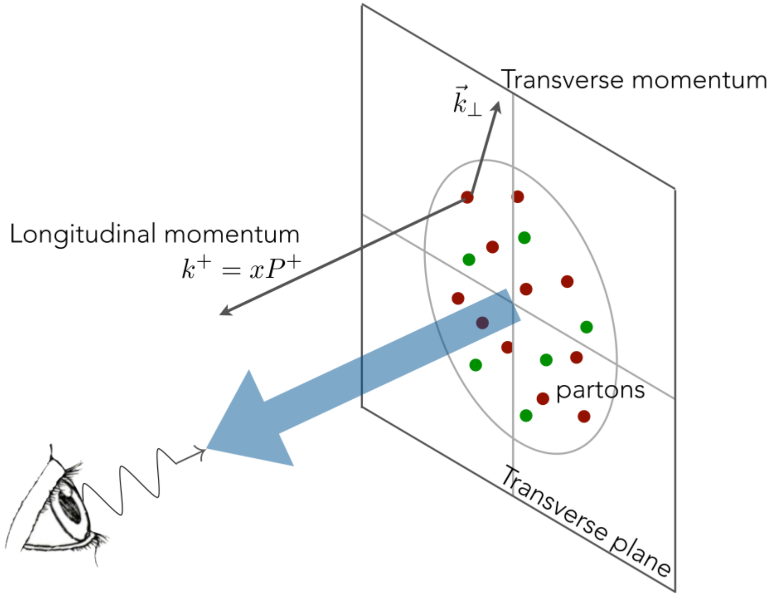
⟷

		quark		
		U	**L**	**T**
nucleon	**U**	$f_1^q(x, \boldsymbol{k}_T^2)$ **number density**		$h_1^{\perp q}(x, \boldsymbol{k}_T^2)$ Boer-Mulders
	L		$g_1^q(x, \boldsymbol{k}_T^2)$ helicity	$h_{1L}^{\perp q}(x, \boldsymbol{k}_T^2)$ worm-gear L
	T	$f_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ Sivers	$g_{1T}^q(x, \boldsymbol{k}_T^2)$ worm-gear T	$h_1^q(x, \boldsymbol{k}_T^2)$ transversity $h_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ pretzelosity

- PDFs – universal (process independent) objects; T-odd PDFs – conditionally universal



⟷

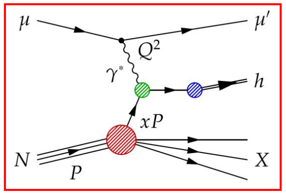


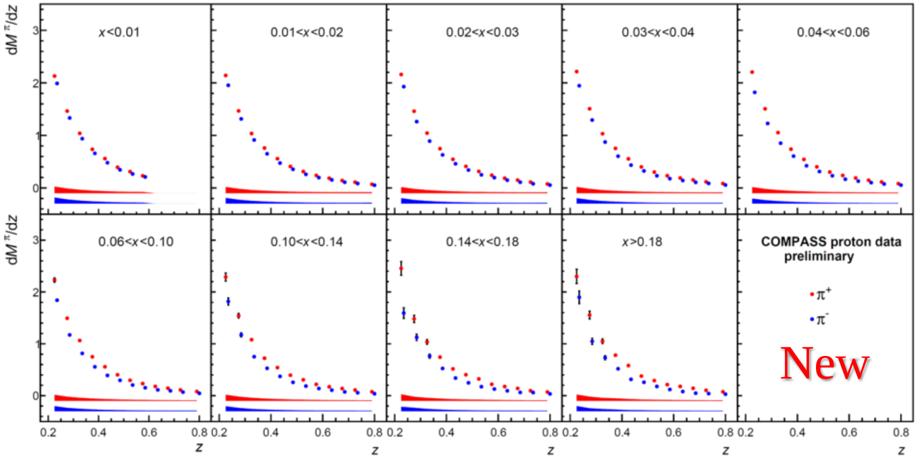
Hadron multiplicities; h±, π± and K± (2016 data)

see e.g. L. Rossi's talk

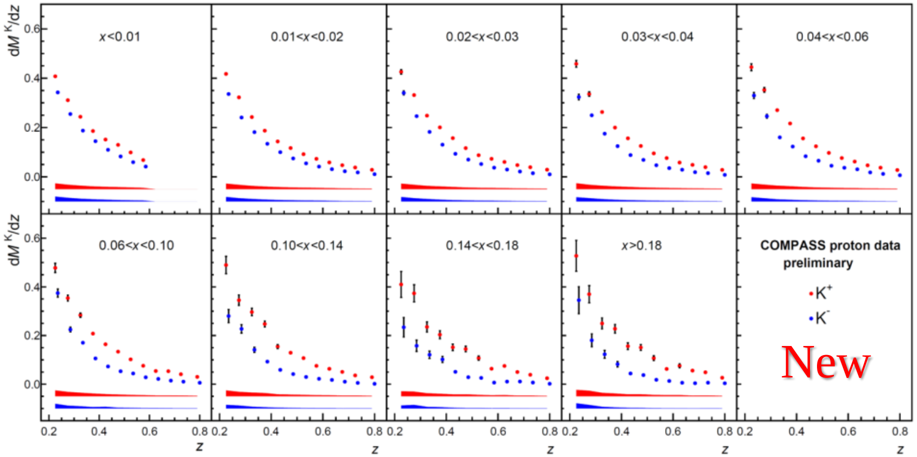
A set of complex corrections:

- Acceptance, rad. corrections, PID, diffractive VMs, etc.

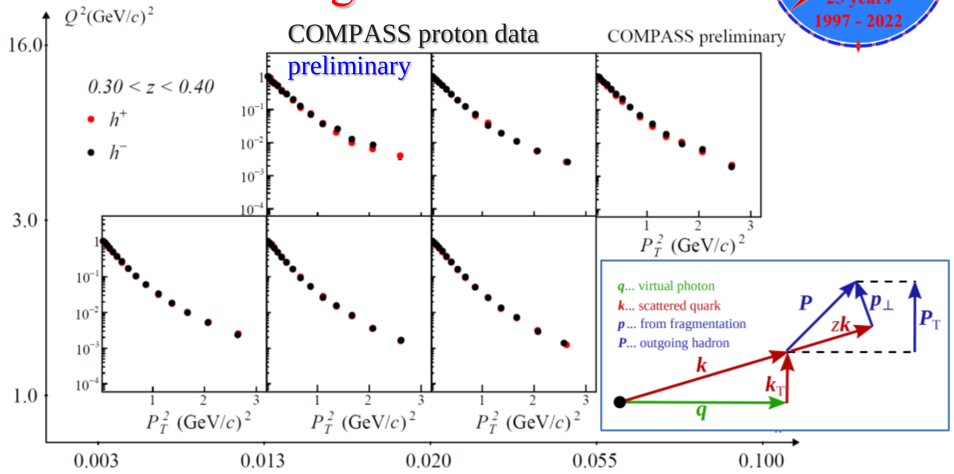




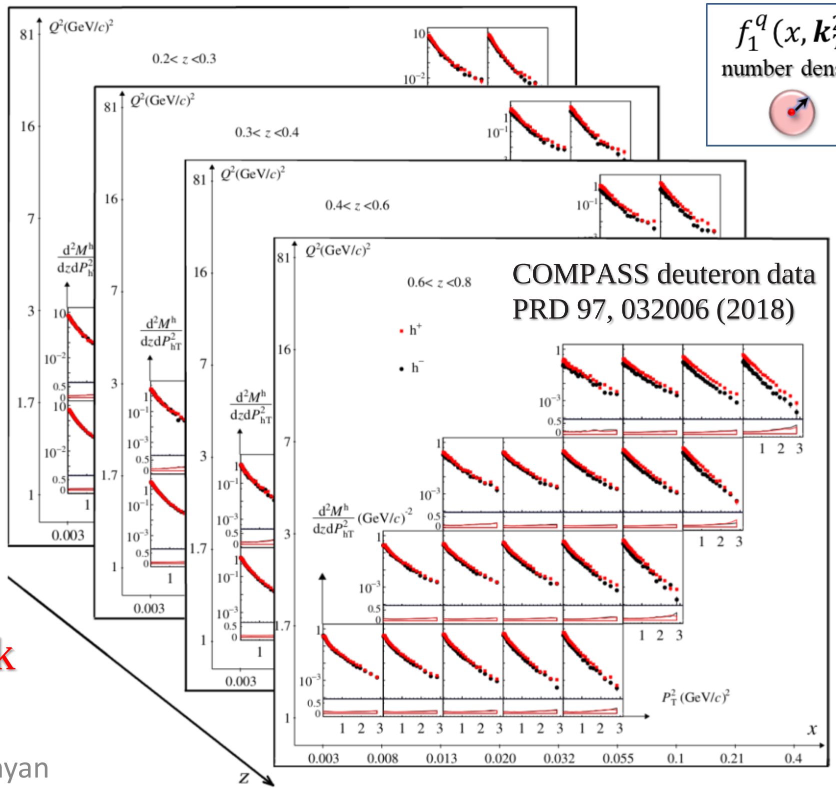
New



New



$f_1^q(x, k_T^2)$
number density

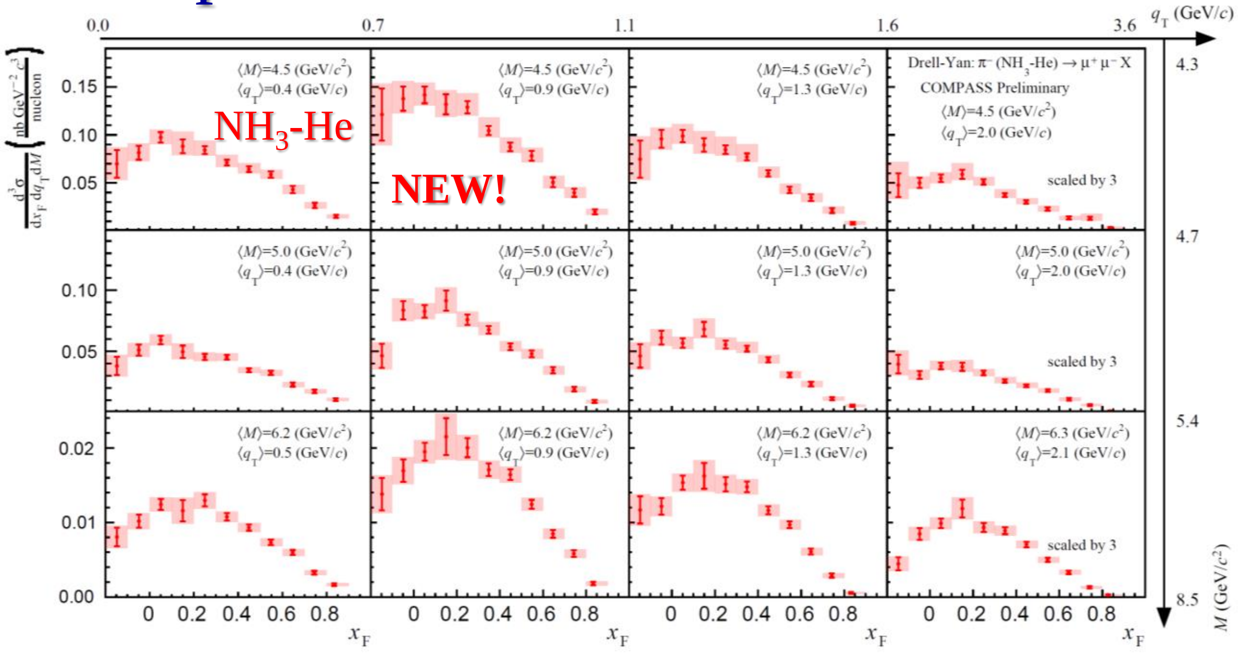


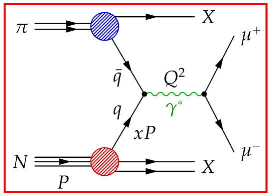
COMPASS deuteron data
PRD 97, 032006 (2018)

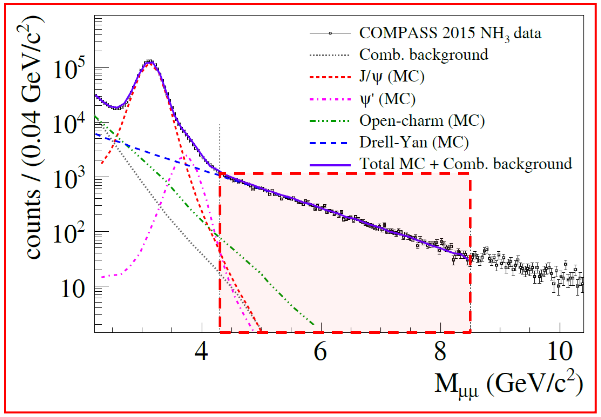
New radiative corrections see M. Stolarski's talk

The article is in a final drafting stage

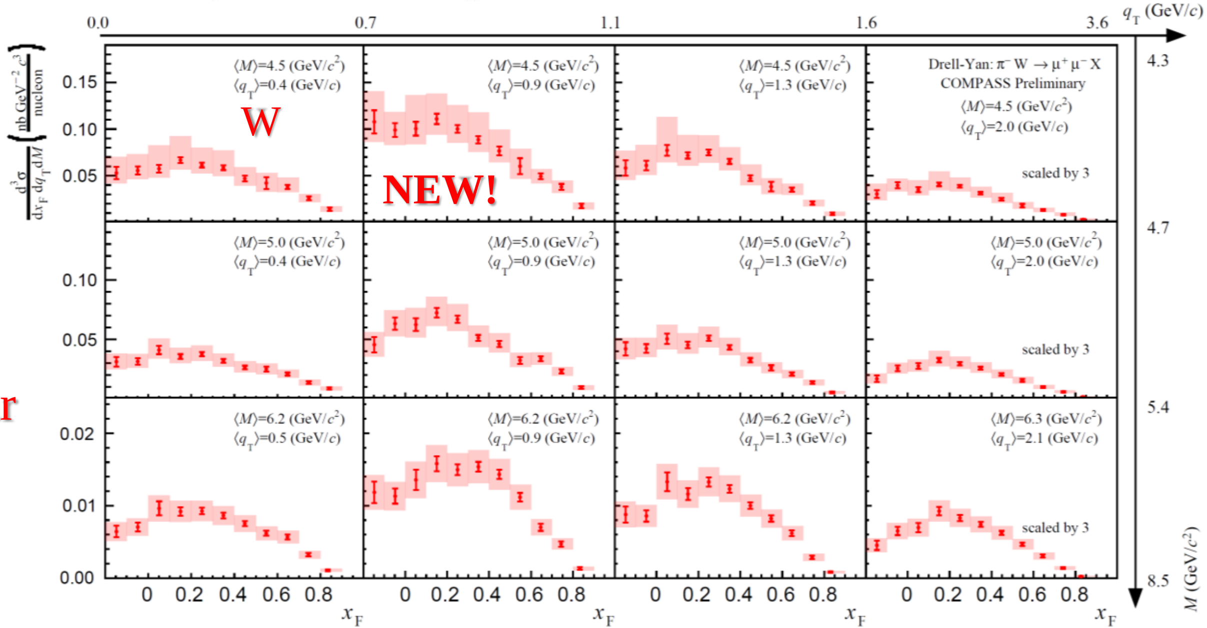
3D unpolarized Drell-Yan cross section on NH_3 and W







- First new results in 30 years!
- Data from light/heavy targets
  - NH_3-He, Al, W
  - Nuclear dependence
- 1D/2D/3D representations x_F:q_T:M
- Unique data to access collinear and TMD distributions e.g. pion TMD PDF



see V. Andrieux's talk

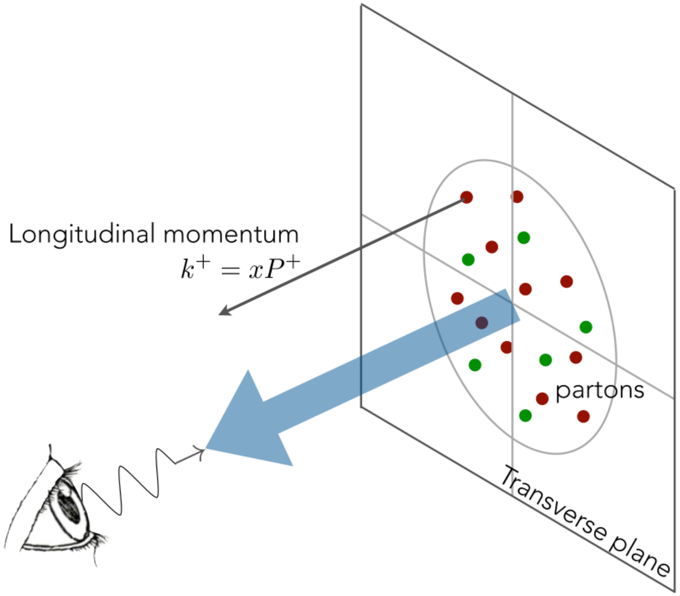
Nucleon spin structure: collinear approach ↔TMDs

		quark		
		U	**L**	**T**
nucleon	**U**	$f_1^q(x)$ number density		
	L		$g_1^q(x)$ **helicity**	
	T			$h_1^q(x)$ transversity

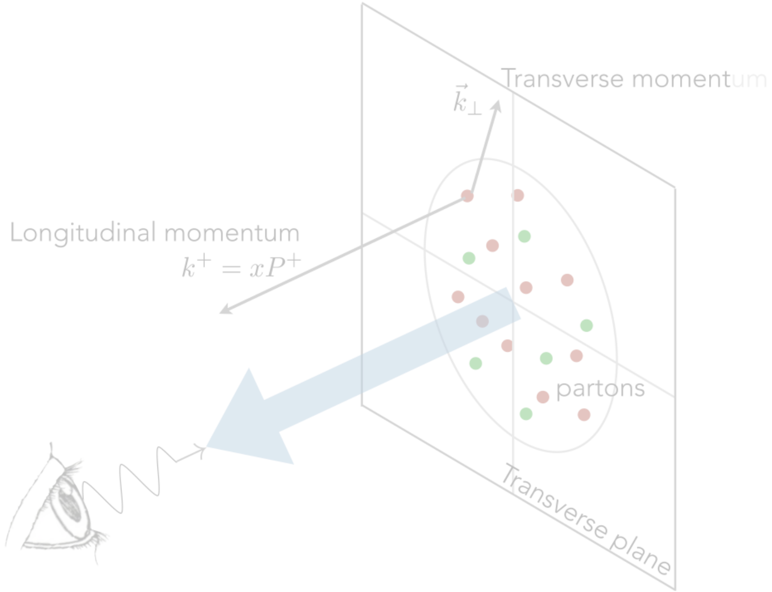
↔

		quark		
		U	**L**	**T**
nucleon	**U**	$f_1^q(x, \boldsymbol{k}_T^2)$ number density		$h_1^{\perp q}(x, \boldsymbol{k}_T^2)$ Boer-Mulders
	L		$g_1^q(x, \boldsymbol{k}_T^2)$ helicity	$h_{1L}^{\perp q}(x, \boldsymbol{k}_T^2)$ worm-gear L
	T	$f_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ Sivers	$g_{1T}^q(x, \boldsymbol{k}_T^2)$ worm-gear T	$h_1^q(x, \boldsymbol{k}_T^2)$ transversity $h_{1T}^{\perp q}(x, \boldsymbol{k}_T^2)$ pretzelosity

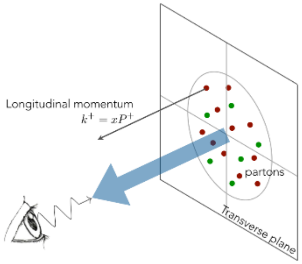
- PDFs – universal (process independent) objects; T-odd PDFs – conditionally universal

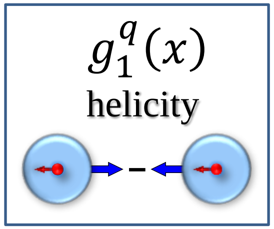


↔



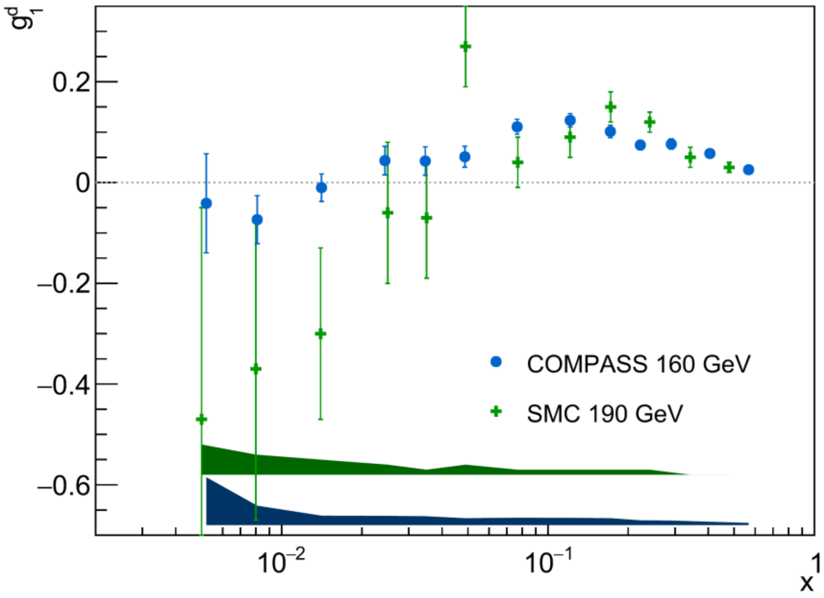
Nucleon spin structure: helicity $g_{1,d}^{q}(x)$

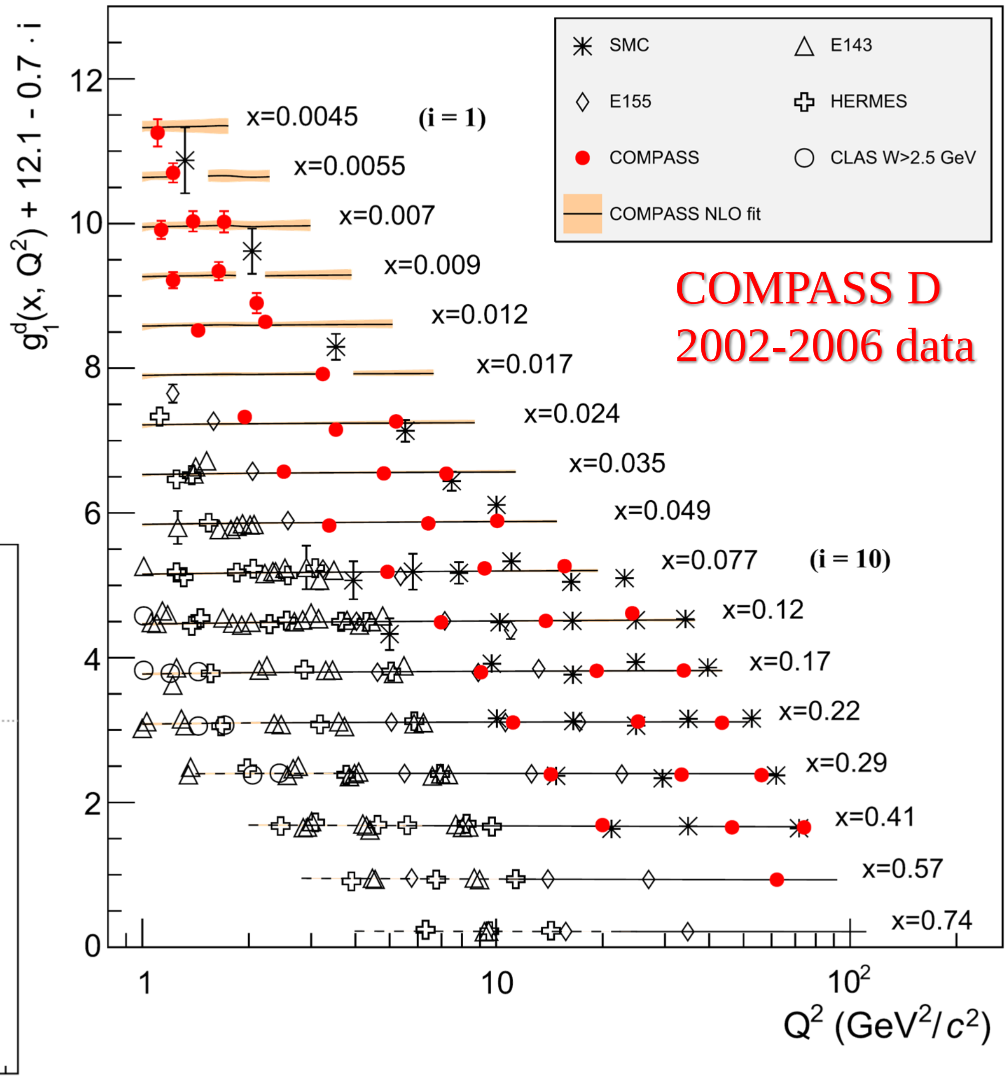



$g_1^q(x)$
helicity

COMPASS PLB 769(2017) 34

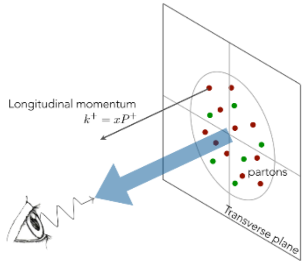
- COMPASS contribution:
  lowest x and highest Q^2 regions

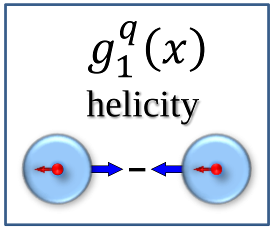




COMPASS D
2002-2006 data

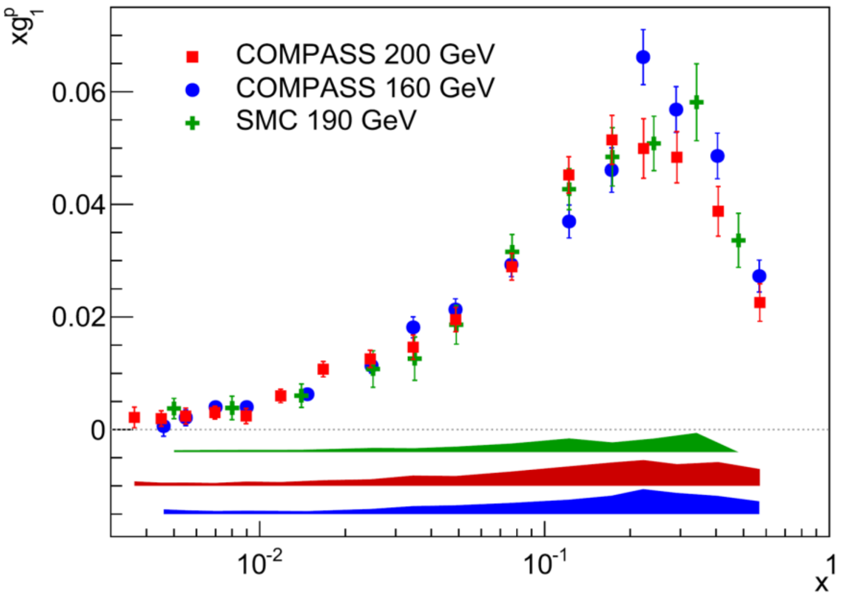
Nucleon spin structure: helicity $g_{1,p}^{q}(x)$



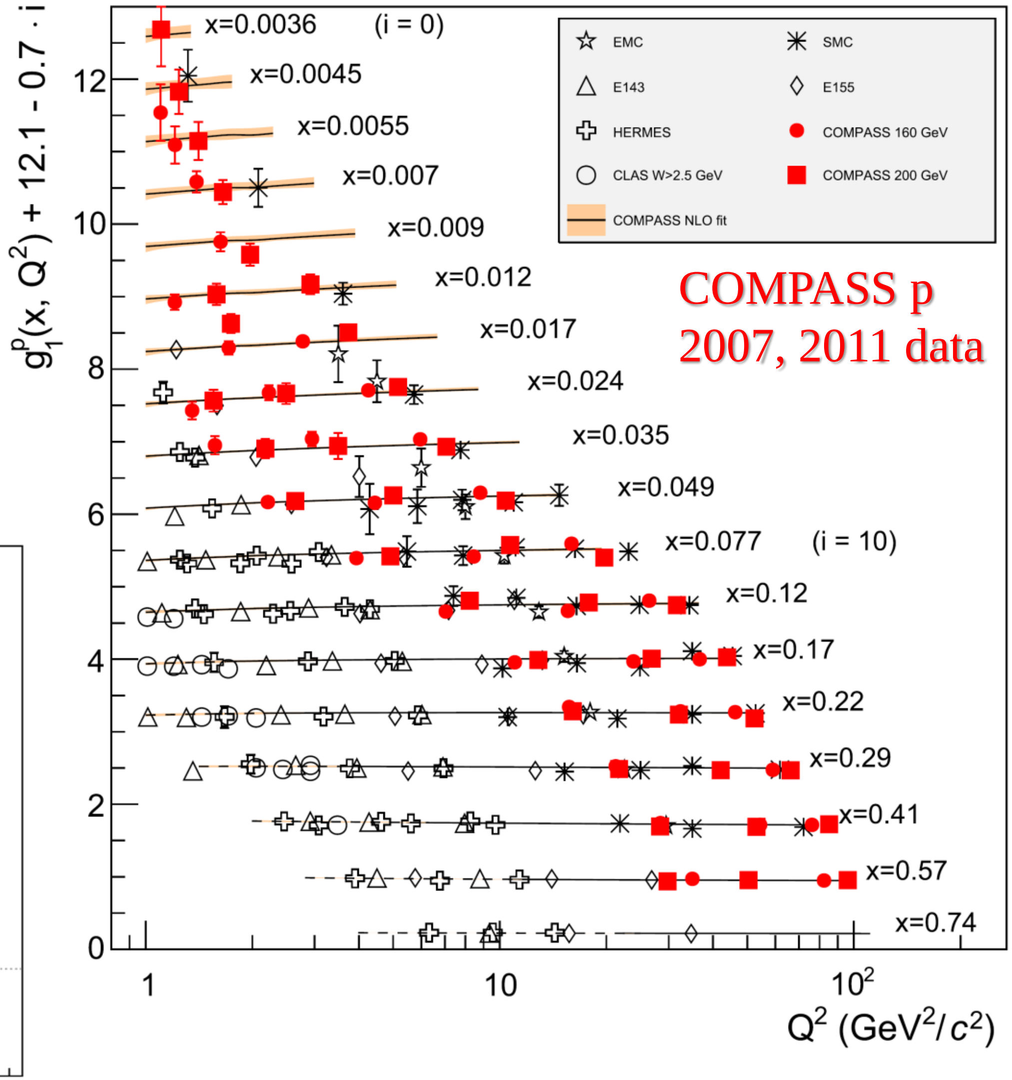

$g_1^q(x)$

helicity

- COMPASS contribution:
  lowest x and highest Q^2 regions
- Both deuteron and proton target data

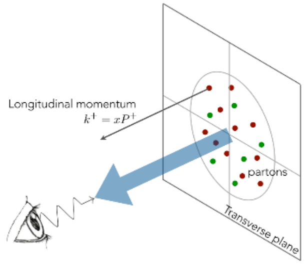


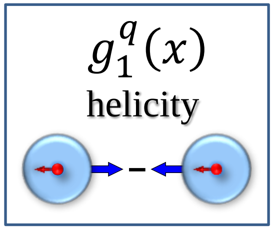
COMPASS PLB 753(2016)18



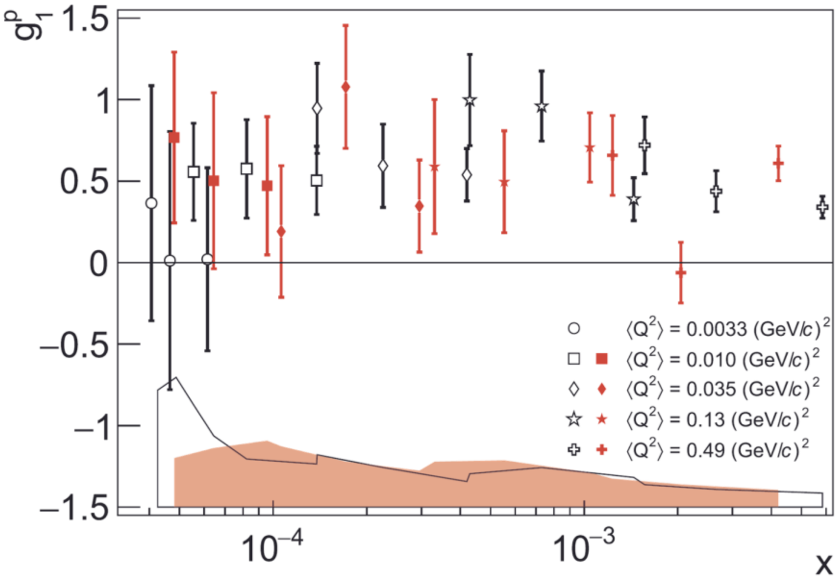
COMPASS p
2007, 2011 data

Nucleon spin structure: helicity $g_{1,p}^{q}(x)$

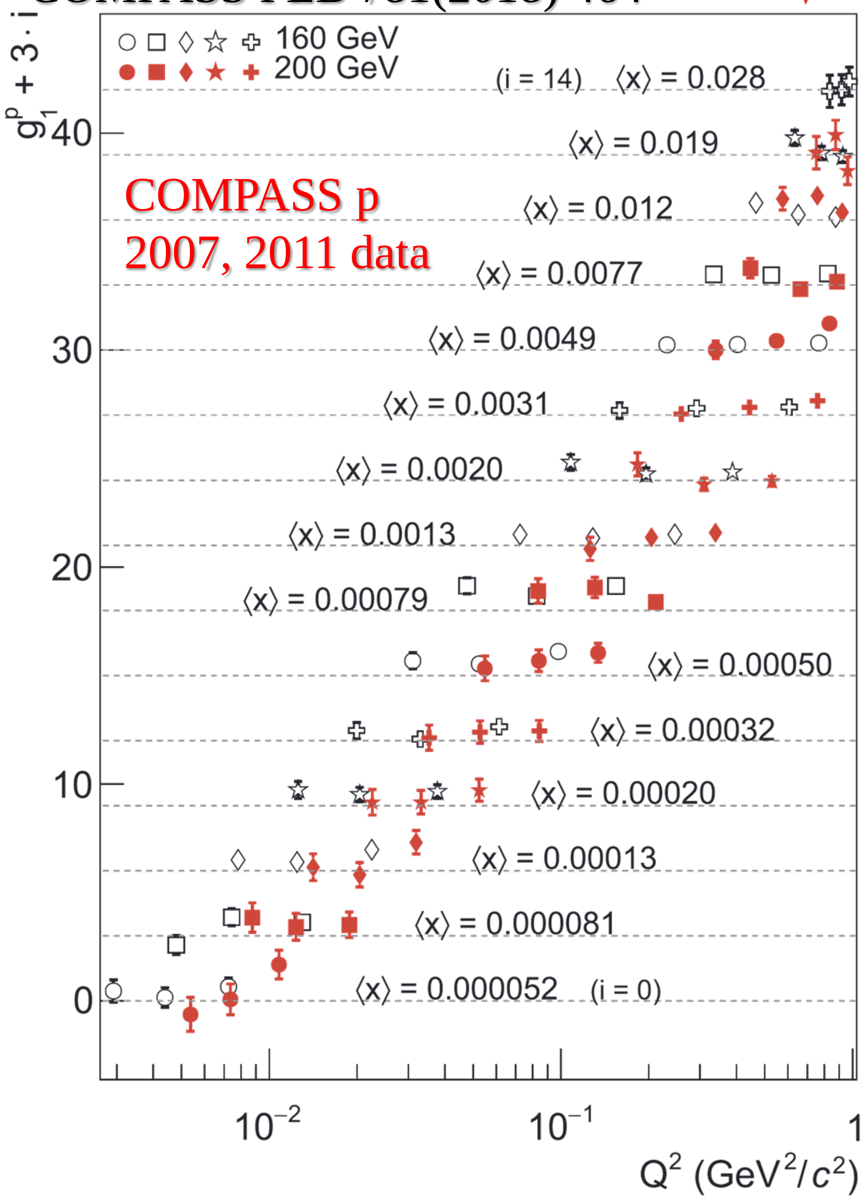




- COMPASS contribution:
  lowest x and highest Q^2 regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest x and Q^2 – positive signal for $g_1^p(x)$



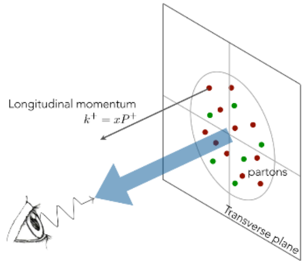
COMPASS PLB 781(2018) 464

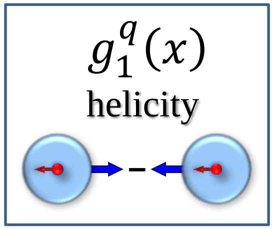


COMPASS p
2007, 2011 data

Nucleon spin structure: helicity $g_{1,d(p)}^{q}(x)$

COMPASS
25 years
1997 - 2022



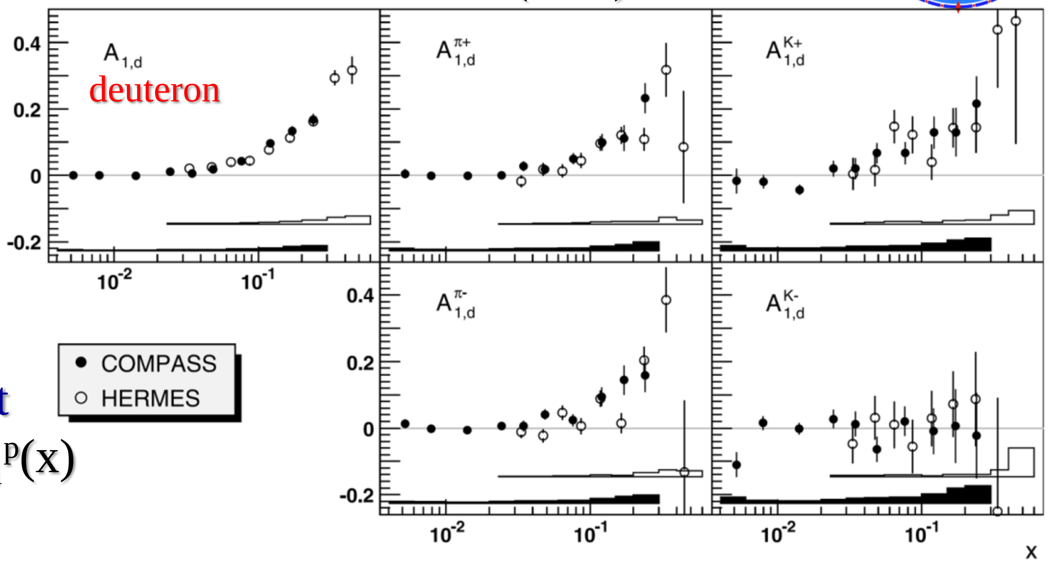


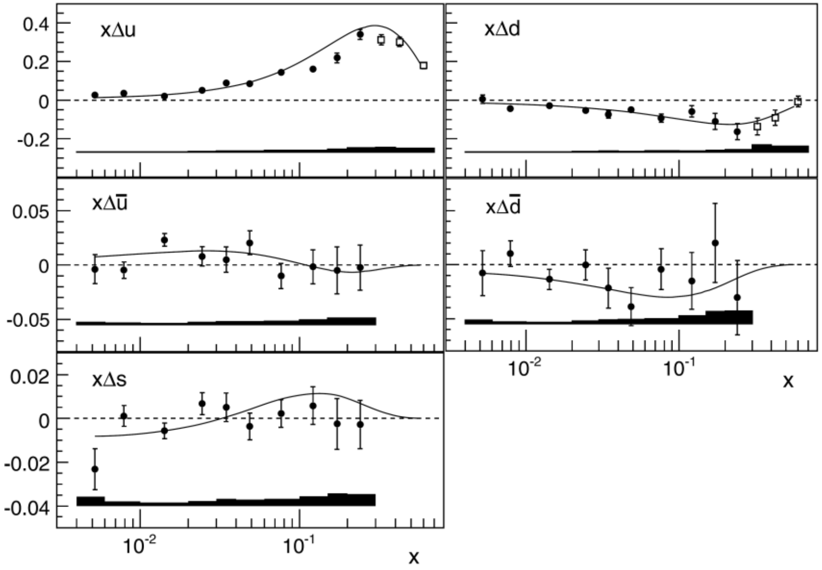
$g_1^q(x)$

helicity

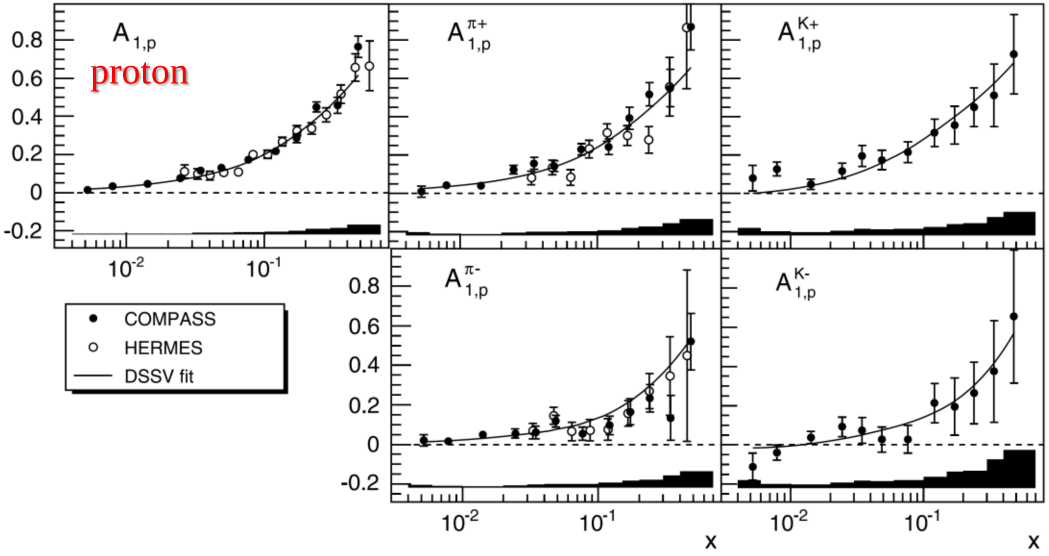
- COMPASS contribution:
  lowest x and highest Q^2 regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest x and Q^2 – positive signal for $g_1^p(x)$
- Both inclusive and semi-inclusive measurements – access to flavor

COMPASS PLB 680 (2009) 217

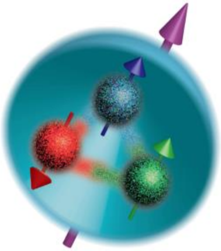




COMPASS PLB 693 (2010) 227

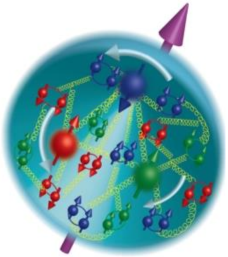


Nucleon spin structure: azimuthal effects



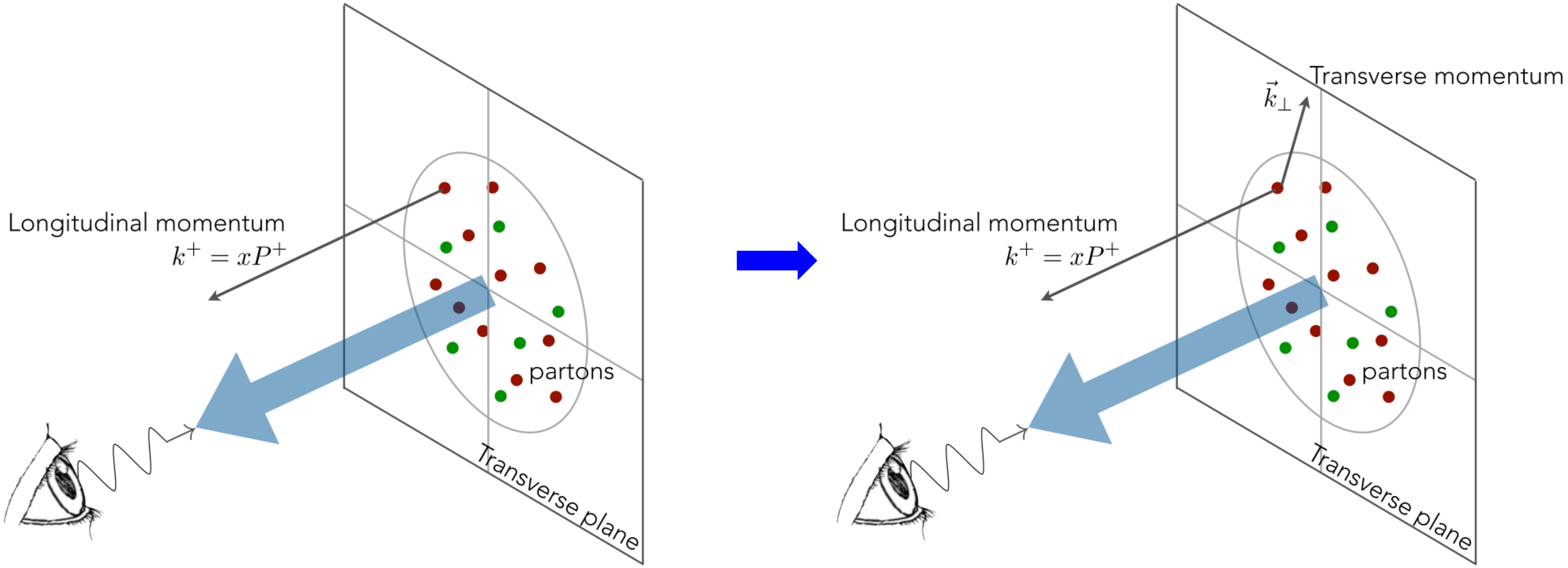
- 1964 Quark model

- 1969 Parton model



- 1973 asymptotic freedom and QCD

- 1978 intrinsic transverse motion of quarks and azimuthal asymmetries

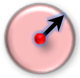


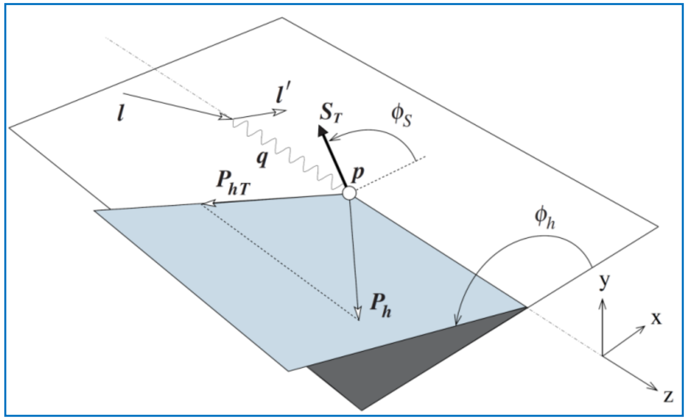
Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times\left(\underbrace{1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}+\ldots\right)$$

$f_1^q(x, \boldsymbol{k}_T^2)$

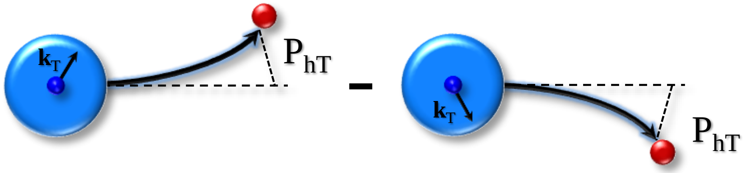
number density



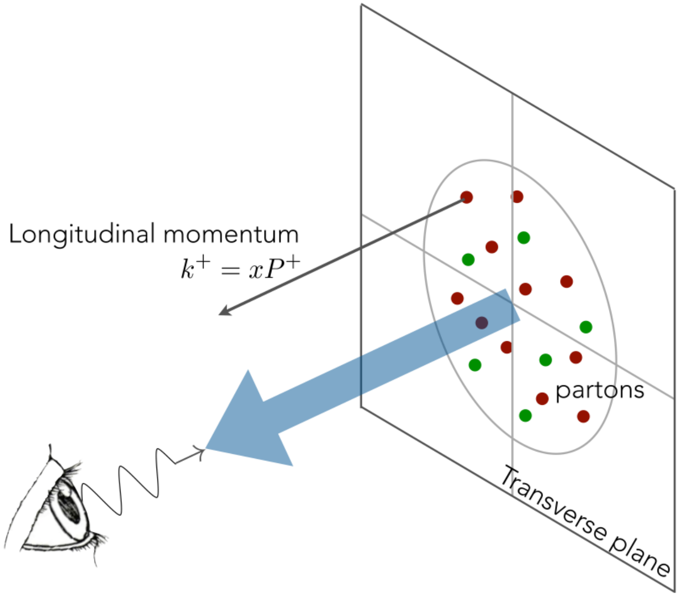


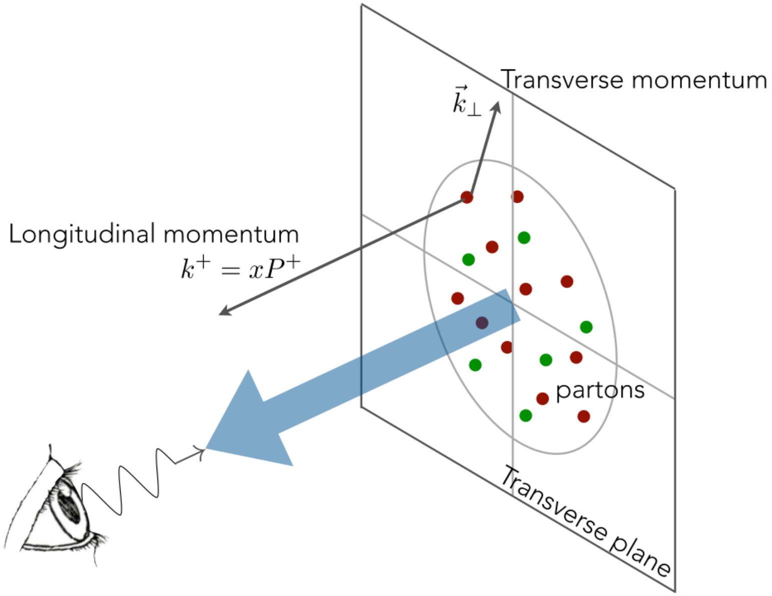
Cahn effect - R. N. Cahn, PLB 78 (1978)

The point that there are azimuthal dependences, which arise from the transverse momenta of the partons was clearly stated in this papers: T.P. Cheng and A. Zee, **Phys. Rev. D6** (1972) 885; F. Ravndal, **Phys. Lett. 43B** (1973) 301.R.L. Kingsley, **Phys. Rev. D10** (1974) 1580; A.M. Kotsinyan, **Teor. Mat. Fiz. 24** (1975) 206;



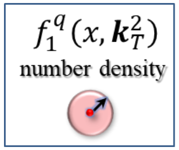
$$k_T \rightarrow \cos\varphi_q \rightarrow \cos\varphi_h$$

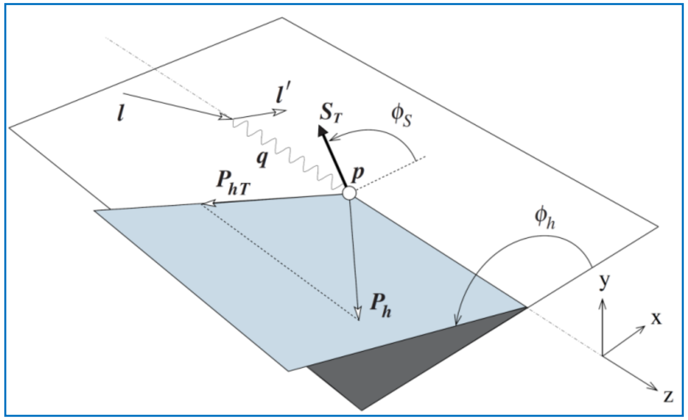


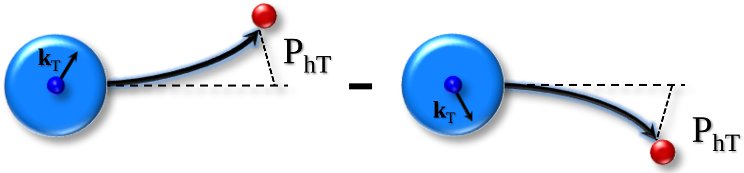


Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_hd\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times\left(1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}+\ldots\right)$$


$f_1^q(x,\boldsymbol{k}_T^2)$
number density



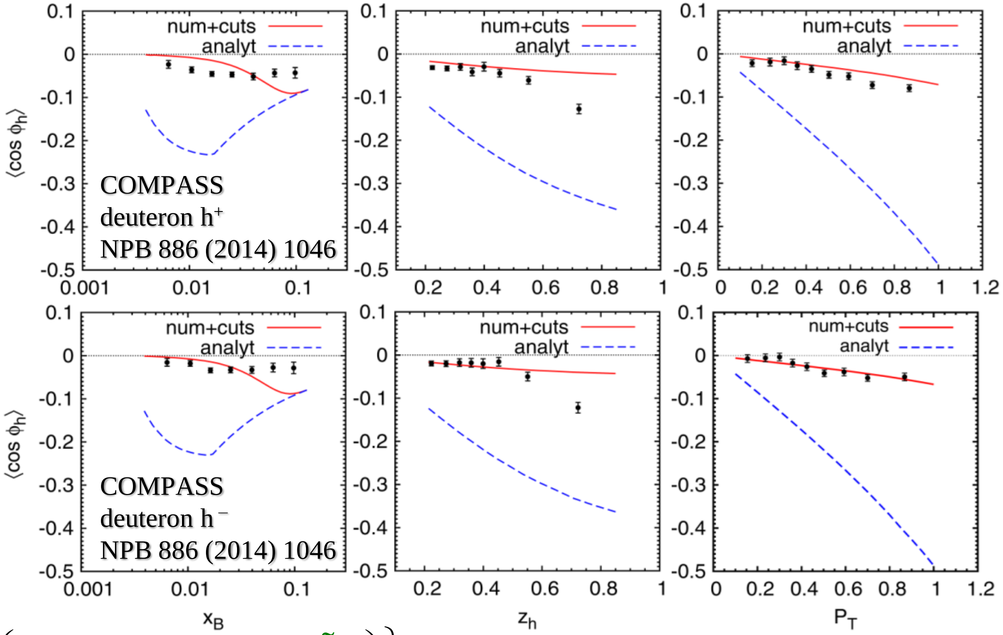


As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

As of 2023 – complex SF (twist-2/3 functions)

- Measurements by different experiments

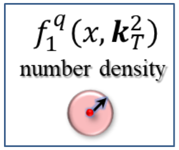


$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}C\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xhH_{1q}^{\perp h}+\frac{M_h}{M}f_1^q\frac{\tilde{D}_q^{\perp h}}{z}\right)-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf^{\perp q}D_{1q}^h+\frac{M_h}{M}h_1^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}$$

Cahn effect in SIDIS

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}+\dots\right)$$



$f_1^q(x,\boldsymbol{k}_T^2)$

number density

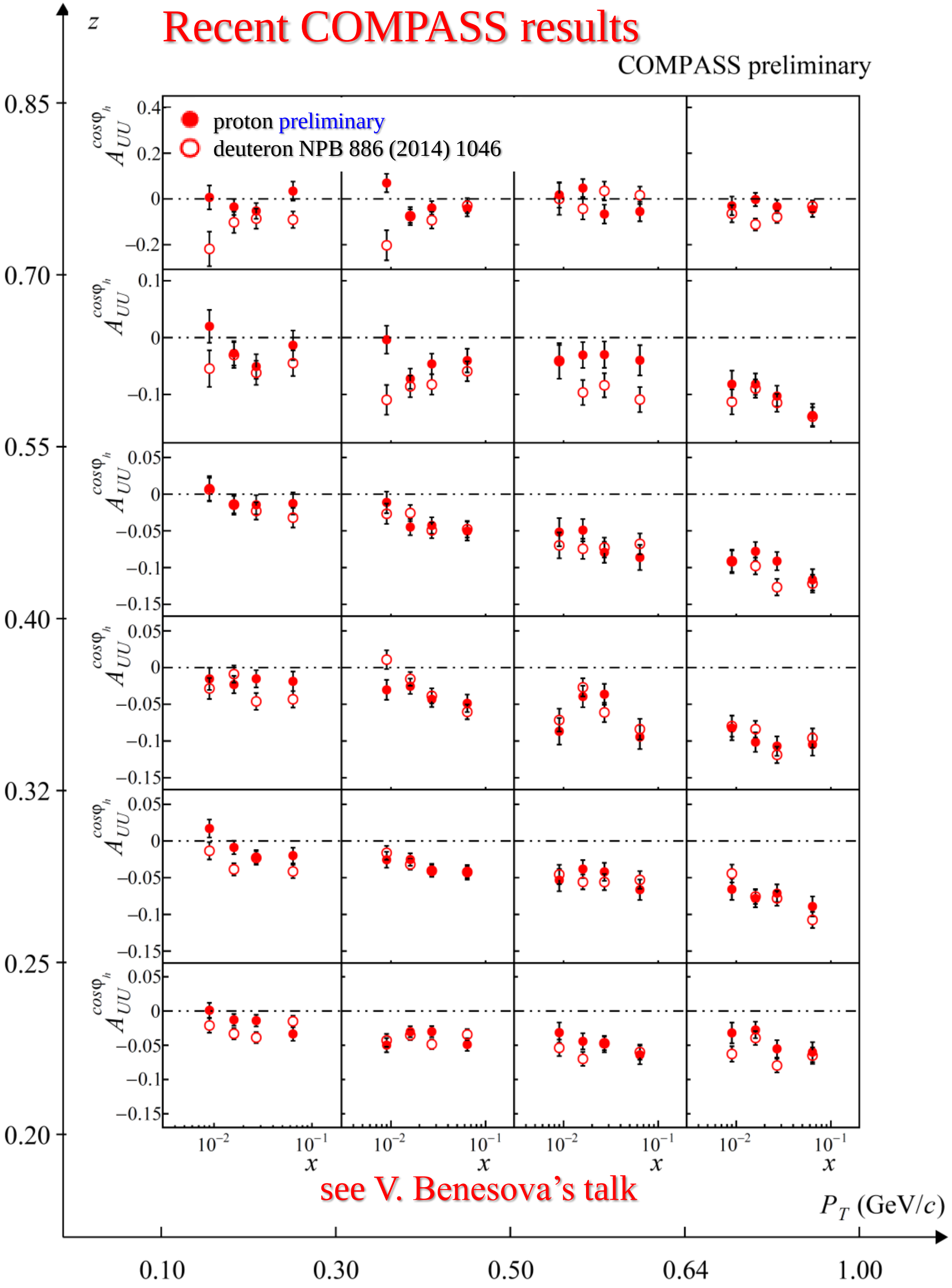
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

As of 2023 – complex SF (twist-2/3 functions)

- Measurements by different experiments
- Complex multi-D kinematic dependences
    - So far, no comprehensive interpretation

Recent COMPASS results



see V. Benesova's talk

Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right) \times\left(\underbrace{1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}} +\ldots\right)$$

Cahn effect

$f_1^q(x,\boldsymbol{k}_T^2)$

number density

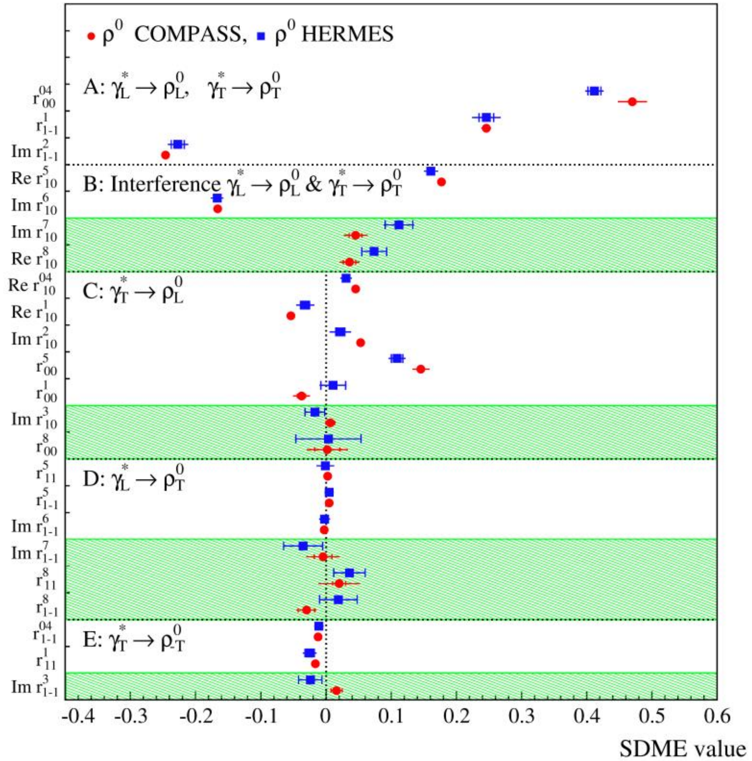
As of 1978 – simplistic kinematic effect:

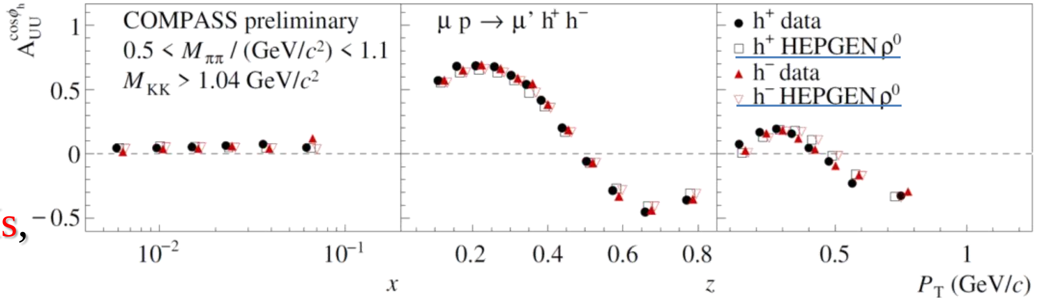
- non-zero k_T induces an azimuthal modulation

As of 2023 – complex SF (twist-2/3 functions)

- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.

COMPASS, EPJC (2023) 83 924



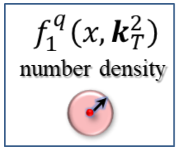


$\cos\phi_h$ amplitude of the radiative corrections

Cahn effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\underbrace{\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h}_{\text{Cahn effect}}+\dots\right)$$


$f_1^q(x,\boldsymbol{k}_T^2)$

number density

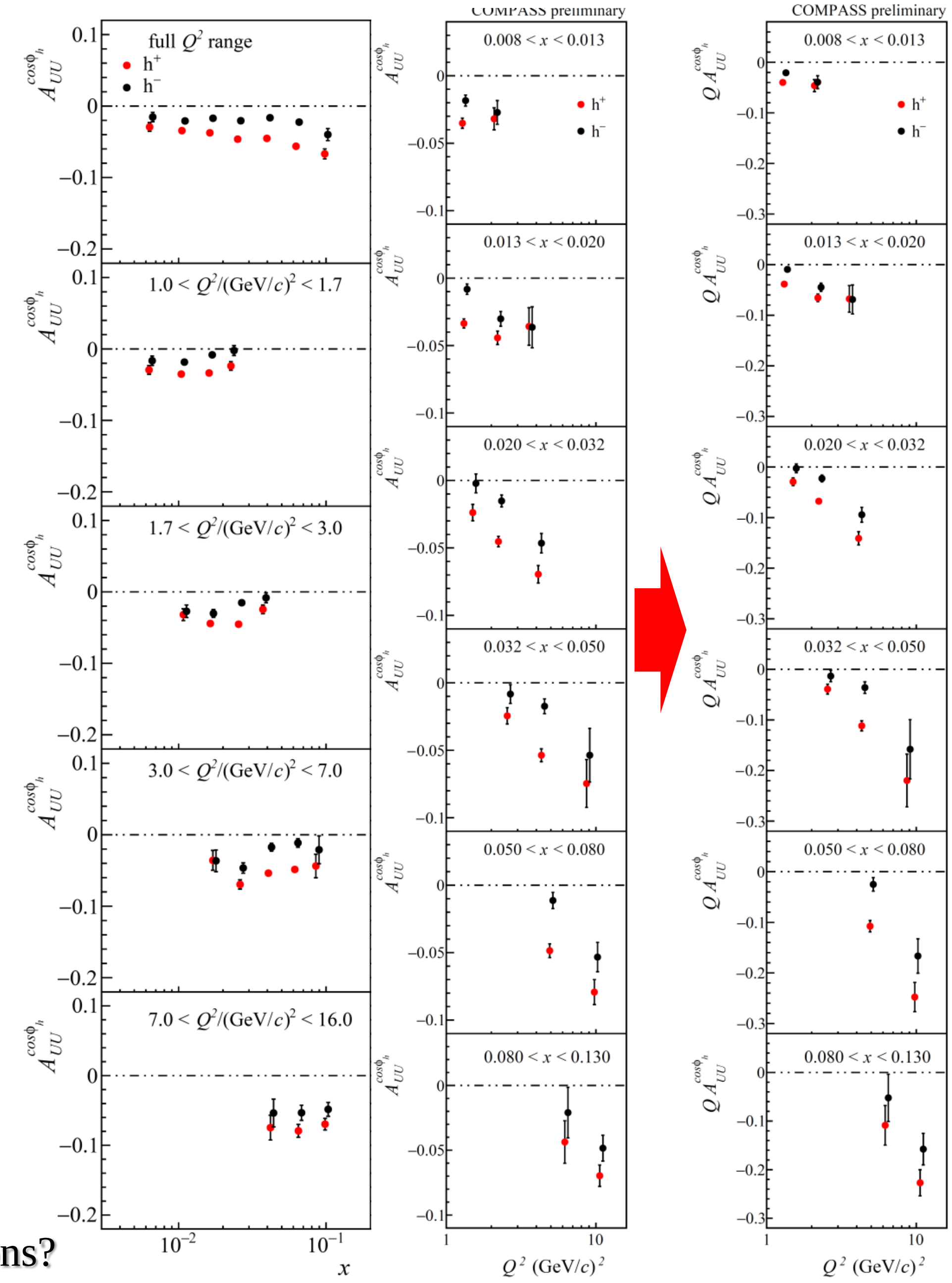
As of 1978 – simplistic kinematic effect:

- non-zero k_T induces an azimuthal modulation

As of 2023 – complex SF (twist-2/3 functions)

- Measurements by different experiments
- Complex multi-D kinematic dependences
  - So far, no comprehensive interpretation
- A set of complex corrections:
  - Acceptance, diffractively produced VMs, radiative corrections (RC), etc.
- Strong Q^2 dependence – unexplained
  - Do not seem to come from RCs
  - Transition between TMD ↔ collinear regions?

Recent COMPASS results



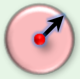
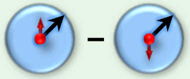
see V. Benesova's talk

Boer-Mulders effect in SIDIS

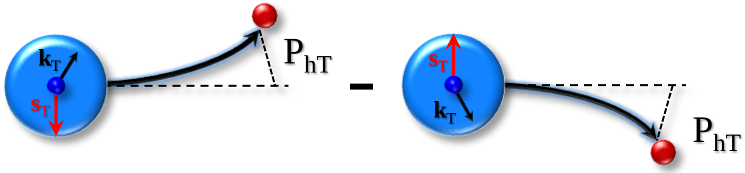
$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} =$$

$$\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\ldots\right)$$

Quark Nucleon	U		T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **number density** 		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ **Boer-Mulders** 

Arises due to the correlation between quark transverse spin and intrinsic transverse momentum



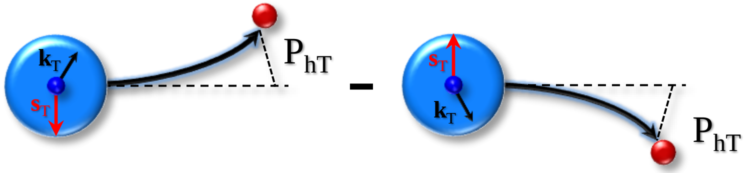
$$F_{UU}^{\cos 2\phi_h} = C\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)-\boldsymbol{p}_T\cdot\boldsymbol{k}_T}{MM_h}h_1^{\perp q}H_{1q}^{\perp h}\right]$$

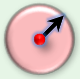
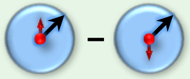
Boer-Mulders effect in SIDIS

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

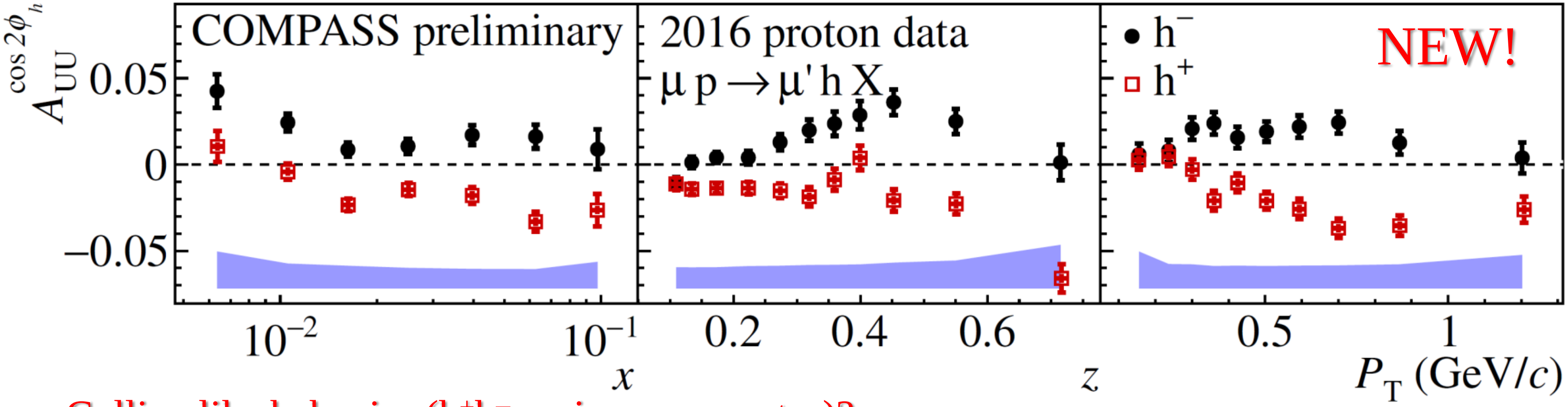
$$\times\left(1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h+\ldots\right)$$

Arises due to the correlation between quark transverse spin and intrinsic transverse momentum



Quark / Nucleon	U		T
U	$f_1^q(x,\boldsymbol{k}_T^2)$ **number density** 		$h_1^{\perp q}(x,\boldsymbol{k}_T^2)$ **Boer-Mulders** 

$$F_{UU}^{\cos 2\phi_h} = C\left[-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T\right)-\boldsymbol{p}_T\cdot\boldsymbol{k}_T}{MM_h}h_1^{\perp q}H_{1q}^{\perp h}\right]$$



- Collins-like behavior (h^+h^- - mirror symmetry)?

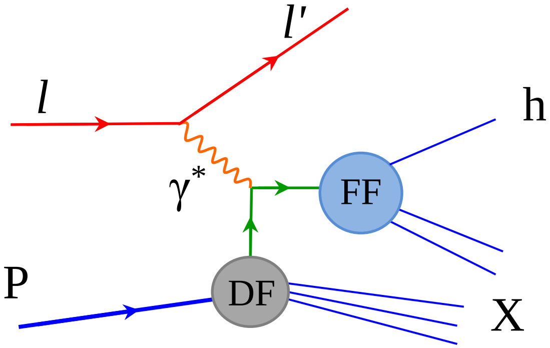
see V. Benesova's talk

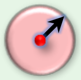
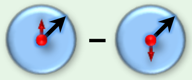
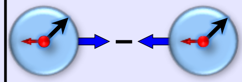
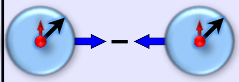
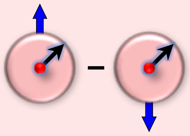
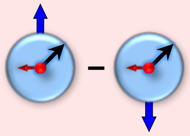
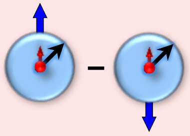
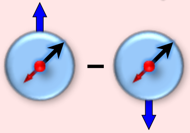
SIDIS x-section and TMDs at twist-2

COMPASS
25 years
1997 - 2022

All measured by COMPASS

$$
\begin{aligned}
\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = &\left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)\\
\times \Bigg\{ & 1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h\\
&+\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h\\
&+S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right]\\
&+S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right]\\
&+\mathrm{S_T}\left[\begin{array}{l}
A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S)\\
+\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S)\\
+\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\\
+\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S\\
+\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)
\end{array}\right]\\
&+\mathrm{S_T}\lambda\left[\begin{array}{l}
\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\\
+\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S\\
+\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)
\end{array}\right]\Bigg\}
\end{aligned}
$$



Quark / Nucleon	U	L	T
U	 number density		 Boer-Mulders
L		 helicity	 worm-gear L
T	 Sivers	 Kotzinian-Mulders worm-gear T	 transversity  pretzelosity

↑ spin of the nucleon ↑ spin of the quark ↗ k_T

SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{ 1+\dots \right.$$

$$+\,S_L\left[\sqrt{2\varepsilon\left(1+\varepsilon\right)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right]$$

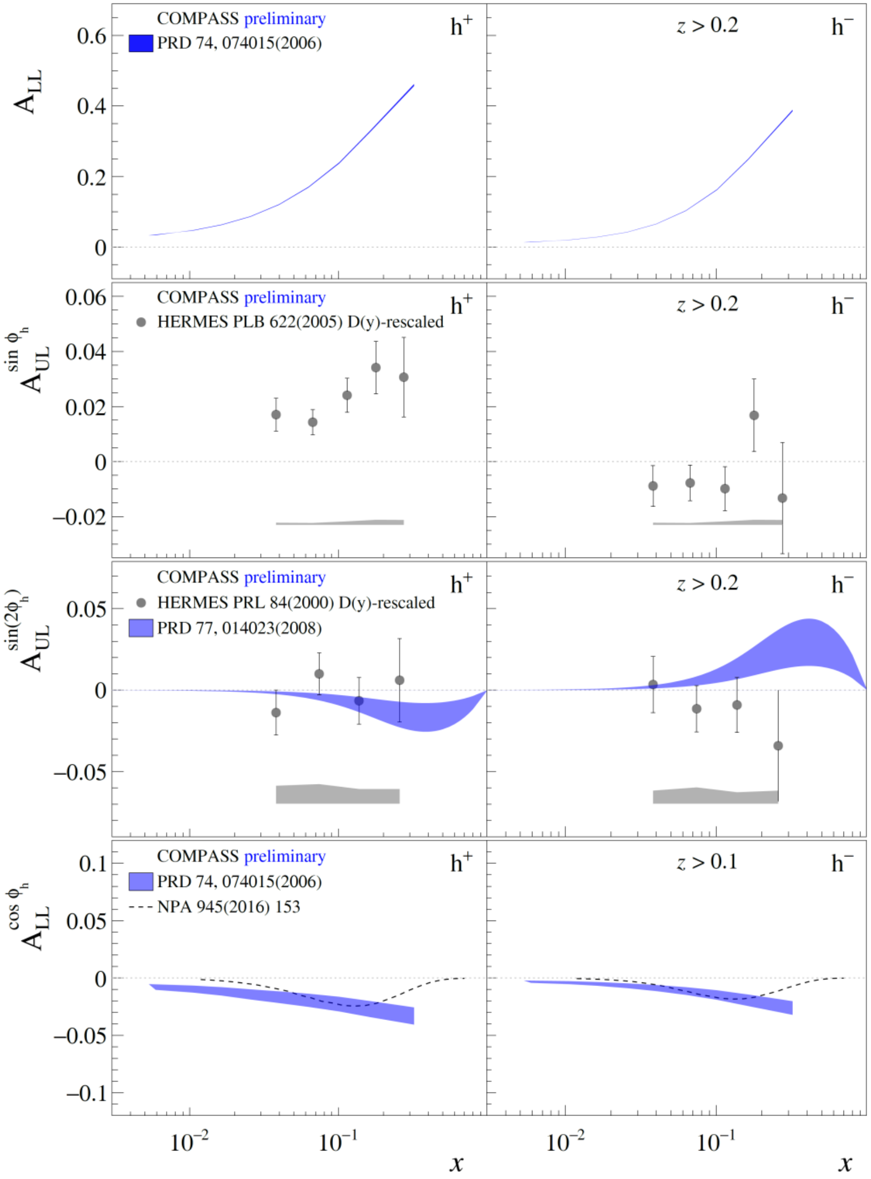
$$\left. +\,S_L\lambda\left[\sqrt{1-\varepsilon^2}\,A_{LL}+\sqrt{2\varepsilon\left(1-\varepsilon\right)}A_{LL}^{\cos\phi_h}\cos\phi_h\right]\right\}$$

$$F_{LL}^{1}=\mathcal{C}\left\{g_{1L}^{q}D_{1q}^{h}\right\}$$

$$F_{UL}^{\sin\phi_h}=\frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xh_L^{q}H_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^{q}\frac{\tilde{G}_q^{\perp h}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf_L^{\perp q}D_{1q}^{h}-\frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{H}_q^{h}}{z}\right)\right\}$$

$$F_{UL}^{\sin 2\phi_h}=\mathcal{C}\left\{-\frac{2\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}\right)\left(\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}\right)-\boldsymbol{p_T}\cdot\boldsymbol{k_T}}{MM_h}h_{1L}^{\perp q}H_{1q}^{\perp h}\right\}$$

$$F_{LL}^{\cos\phi_h}=\frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xe_L^{q}H_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^{q}\frac{\tilde{D}_q^{\perp h}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xg_L^{\perp q}D_{1q}^{h}-\frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{E}_q^{h}}{z}\right)\right\}$$



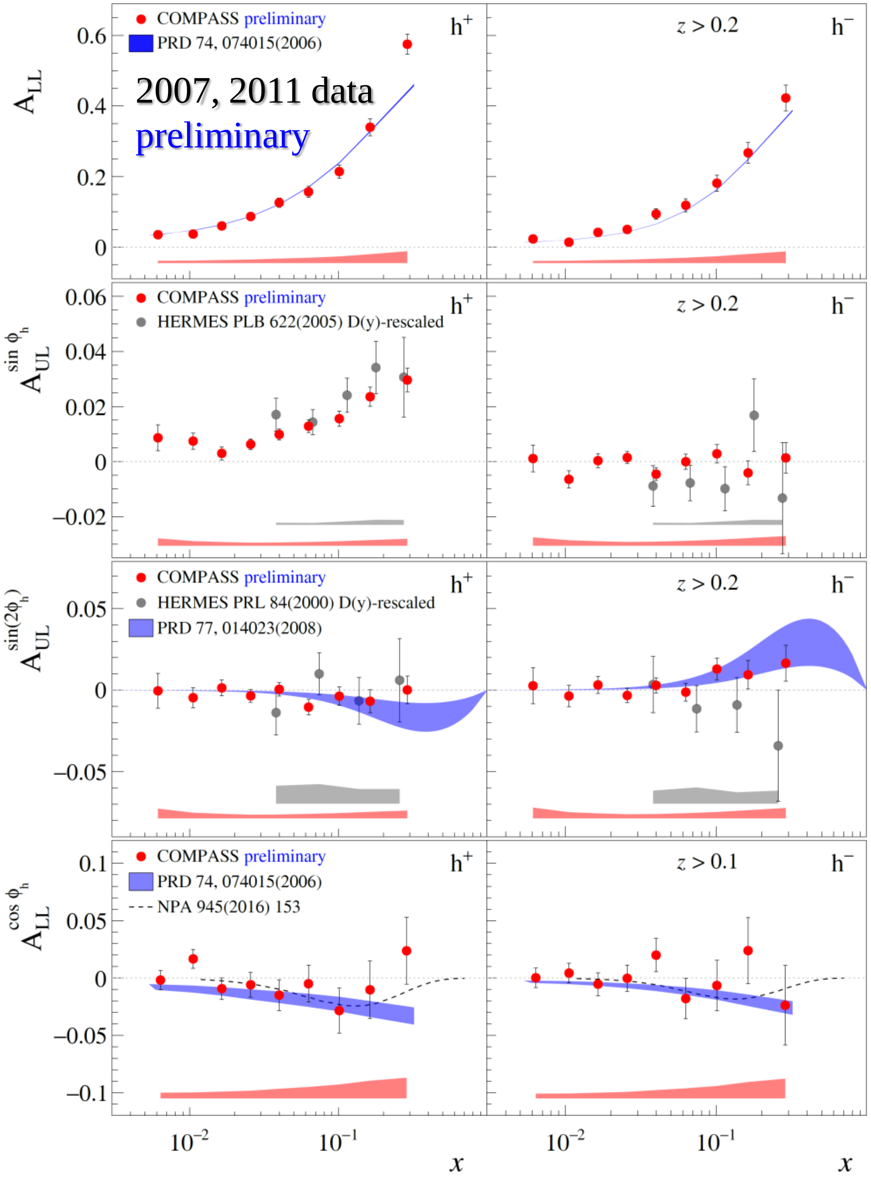
SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\Big\{ \quad 1 + \ldots$$

$$+ S_L \left[\sqrt{2\varepsilon\left(1+\varepsilon\right)} A_{UL}^{\sin\phi_h} \sin\phi_h + \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h\right]$$

$$+ S_L \lambda\left[\sqrt{1-\varepsilon^2} A_{LL} + \sqrt{2\varepsilon\left(1-\varepsilon\right)} A_{LL}^{\cos\phi_h} \cos\phi_h\right]\Big\}$$

B. Parsamyan (for COMPASS) arXiv:1801.01488 [hep-ex]



COMPASS collected large amount of L-SIDIS data

Unprecedented precision for some amplitudes!

$A_{UL}^{\sin\phi_h}$

- Q-suppression, Various different "twist" ingredients
- Sizable TSA-mixing
- Significant h$^+$ asymmetry, clear z-dependence
- h$^-$ compatible with zero

$A_{UL}^{\sin 2\phi_h}$

- Only "twist-2" ingredients
- Additional p$_T$-suppression
- Compatible with zero, in agreement with models
- Collins-like behavior?

$A_{LL}^{\cos\phi_h}$

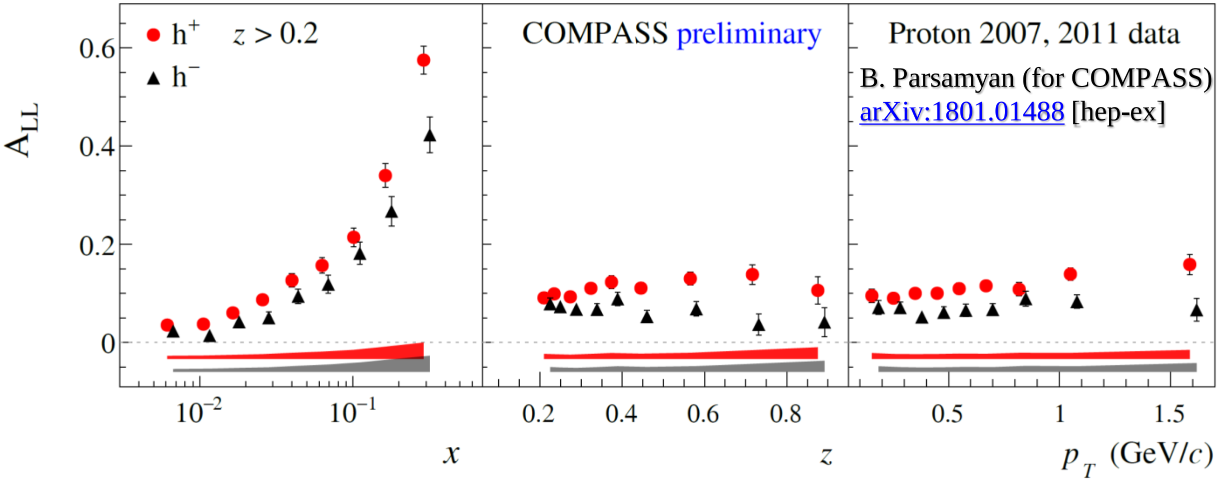
- Q-suppression, Various different "twist" ingredients
- Compatible with zero, in agreement with models

SIDIS: target longitudinal spin dependent asymmetries

$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_L\lambda\sqrt{1-\varepsilon^2}\,A_{LL}+\ldots\right\}$$

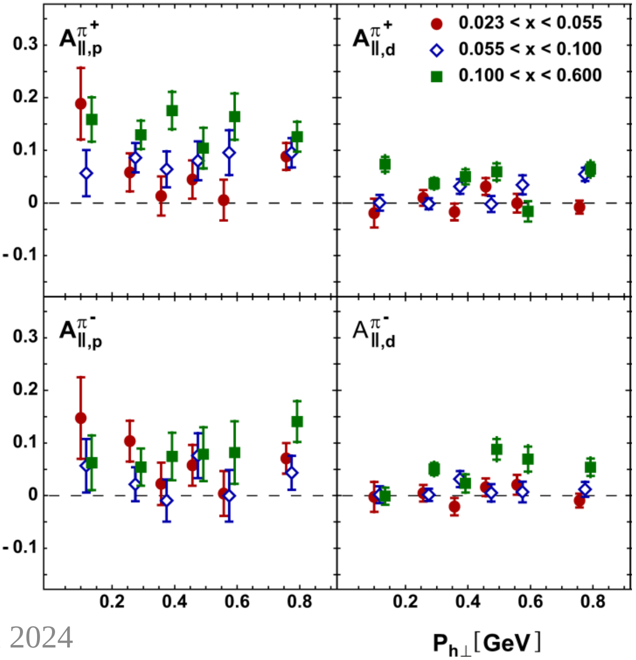
$$\boxed{F_{LL}^1 = \mathcal{C}\left\{g_{1L}^q D_{1q}^h\right\}}$$

- Measurement of (semi-)inclusive $A_1(A_{LL})$ is one of the key physics topics of HERMES/COMPASS
- Large amount of P/D data
- No P_T-dependence observed

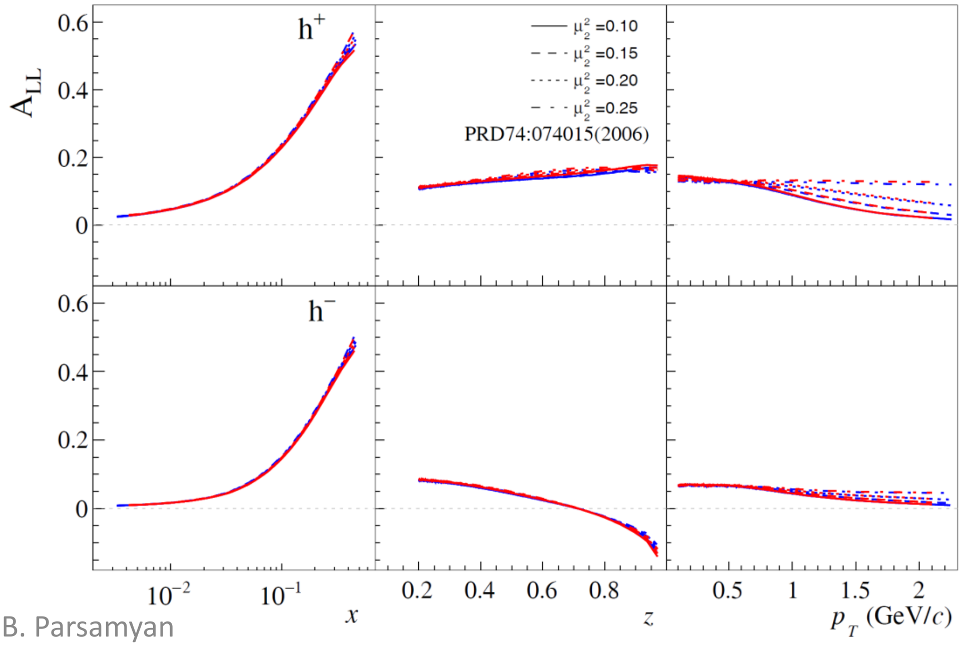


B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]

HERMES: PRD 99, 112001 (2019)



COMPASS Proton-2007, -2011 kinematics

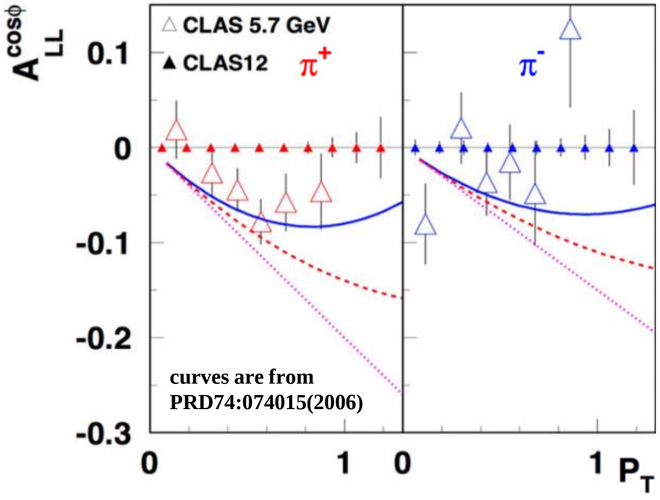


SIDIS: target longitudinal spin dependent asymmetries

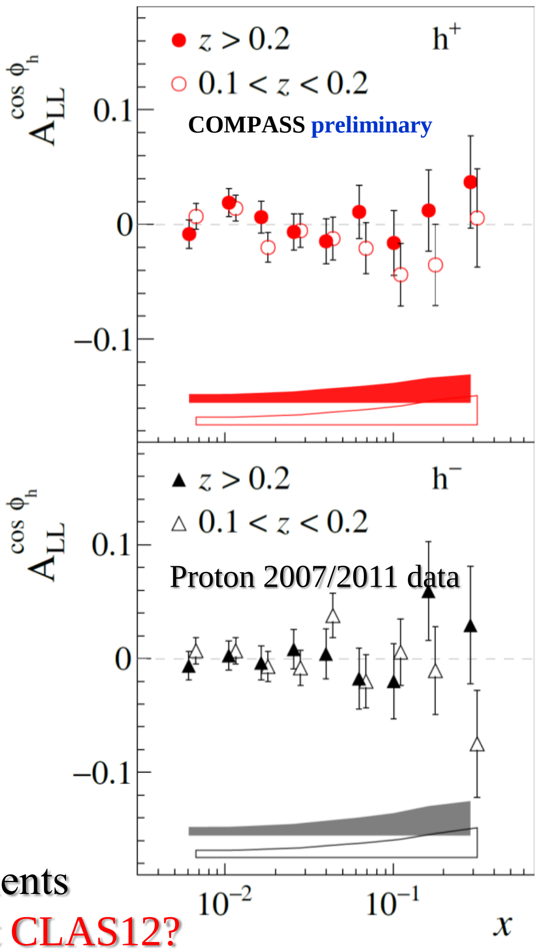
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_L\lambda\sqrt{2\varepsilon\left(1-\varepsilon\right)}A_{LL}^{\cos\phi_h}\cos\phi_h+\ldots\right\}$$

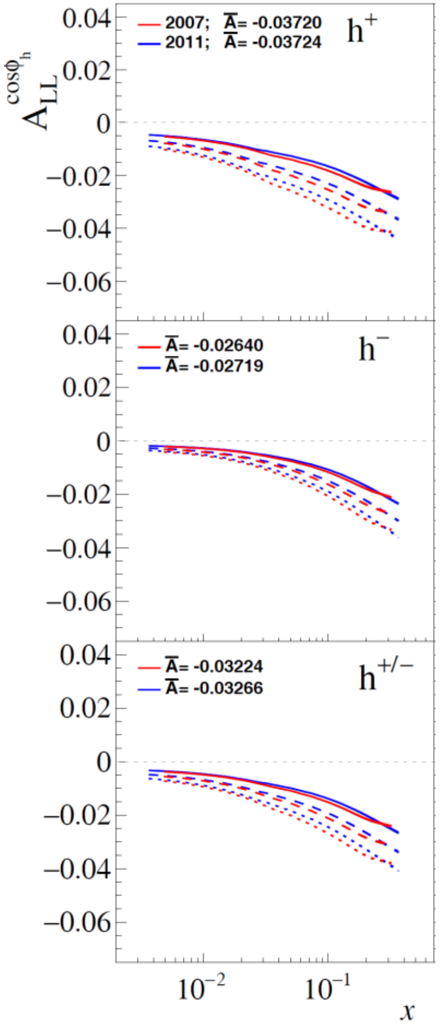
$$\boxed{F_{LL}^{\cos\phi_h}=\frac{2M}{Q}\mathcal{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xe_L^q H_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^q\frac{\tilde{D}_q^{\perp h}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xg_L^{\perp q}D_{1q}^h-\frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{E}_q^h}{z}\right)\right\}}$$

CLAS, PRL 105,262002(2010)



B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]





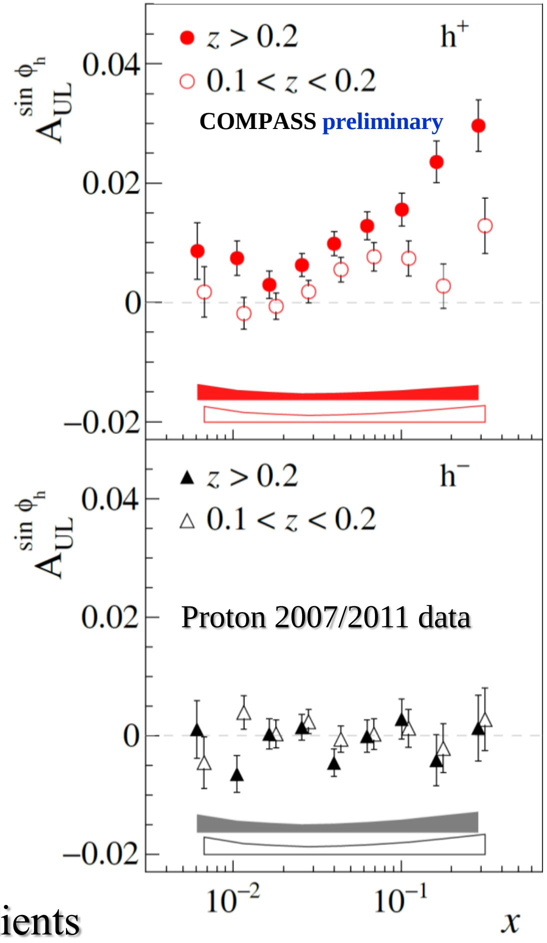
- Q-suppression, various different “twist” ingredients
- Measured to be non zero at CLAS6, what about CLAS12?
- HERMES/COMPASS - small and compatible with zero, in agreement with model predictions

SIDIS: target longitudinal spin dependent asymmetries

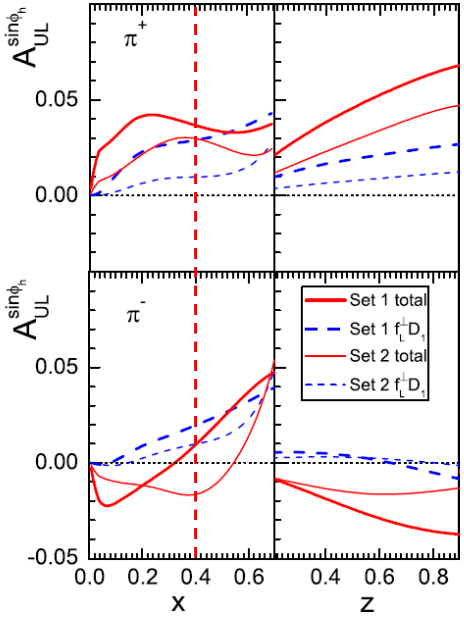
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\; S_L \sqrt{2\varepsilon\left(1+\varepsilon\right)}A_{UL}^{\sin\phi_h}\sin\phi_h+\ldots\right\}$$

$$\boxed{F_{UL}^{\sin\phi_h}=\frac{2M}{Q}\mathbb{C}\left\{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\left(xh_L^q H_{1q}^{\perp h}+\frac{M_h}{M}g_{1L}^q\frac{\tilde{G}_q^{\perp h}}{z}\right)+\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\left(xf_L^{\perp q}D_{1q}^h-\frac{M_h}{M}h_{1L}^{\perp q}\frac{\tilde{H}_q^h}{z}\right)\right\}}$$

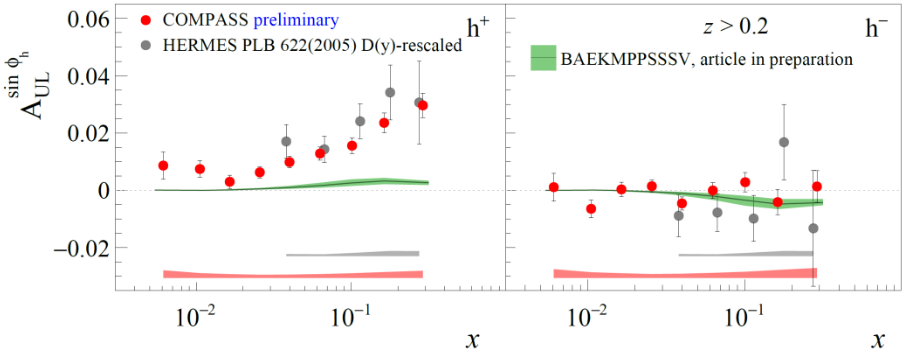
B. Parsamyan (for COMPASS)
arXiv:1801.01488 [hep-ex]



Zhun Lu
Phys. Rev. D 90, 014037(2014)



S. Bastami et al. JHEP 1906 (2019) 007:
"SIDIS in Wandzura-Wilczek-type approximation"



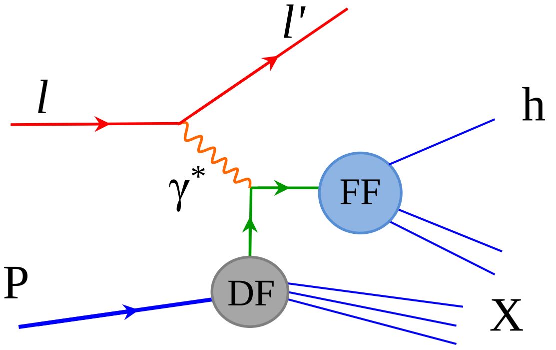
- Q-suppression, various different "twist" ingredients
- Measured to be non zero COMPASS and HERMES
- Non-zero trend for h^+, h^- - compatible with zero, clear *z*-dependence

SIDIS x-section and TMDs at twist-2: TSAs

All measured by COMPASS

$$\frac{d\sigma}{dxdydzdp_T^2d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$$\times\left\{\begin{array}{l}
1+\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\
+\ \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\
+\ S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] \\
+\ S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] \\
+\ S_T\left[\begin{array}{l}
A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\
+\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\
+\ \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\
+\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\
+\ \sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)
\end{array}\right] \\
+\ S_T\lambda\left[\begin{array}{l}
\sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\
+\ \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\
+\ \sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)
\end{array}\right]
\end{array}\right\}$$



$A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_{1T}^{\perp q}\otimes D_{1q}^{h}$ **Sivers**

$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q\otimes H_{1q}^{\perp h}$ **Collins**

$A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}$

$A_{UT}^{\sin(\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_1^q\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^{h}+\ldots\right)$

$A_{UT}^{\sin(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(h_{1T}^{\perp q}\otimes H_{1q}^{\perp h}+f_{1T}^{\perp q}\otimes D_{1q}^{h}+\ldots\right)$

$A_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q\otimes D_{1q}^{h}$

$A_{LT}^{\cos(\phi_s)} \overset{WW}{\propto} Q^{-1}\left(g_{1T}^q\otimes D_{1q}^{h}+\ldots\right)$

$A_{LT}^{\cos(2\phi_h-\phi_s)} \overset{WW}{\propto} Q^{-1}\left(g_{1T}^q\otimes D_{1q}^{h}+\ldots\right)$

Twist-2

Twist-3

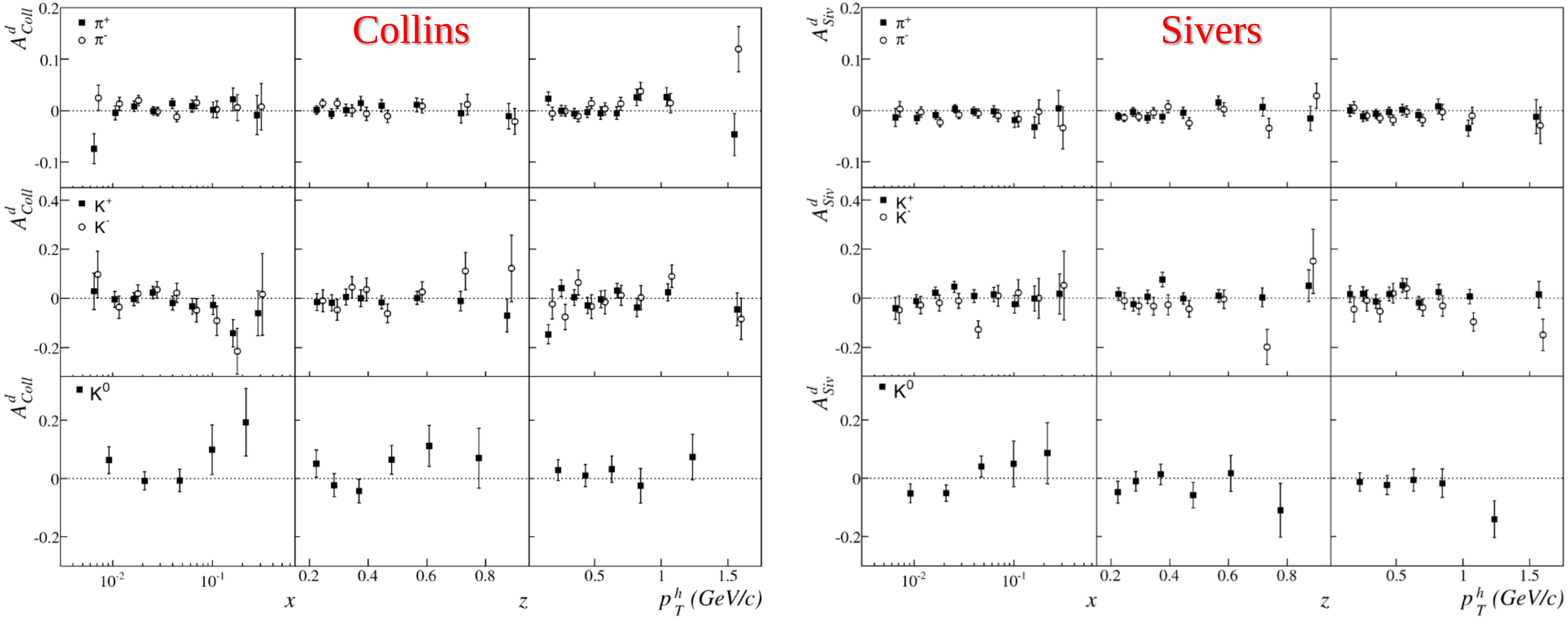
SIDIS TSAs: Collins and Sivers effects (deuteron)

$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_{\mathrm{T}}\,A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+S_{\mathrm{T}}\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)\ldots\right\}$$

$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p_T}}{M_h}\,h_1^q H_{1q}^{\perp h}\right]}$$

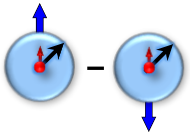
$$\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k_T}}{M}\,f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0}$$

COMPASS PLB 673 (2009) 127



- 1st COMPASS deuteron measurements
- Collins and Sivers asymmetries compatible with zero within uncertainties.

SIDIS TSAs: Collins effect and Transversity

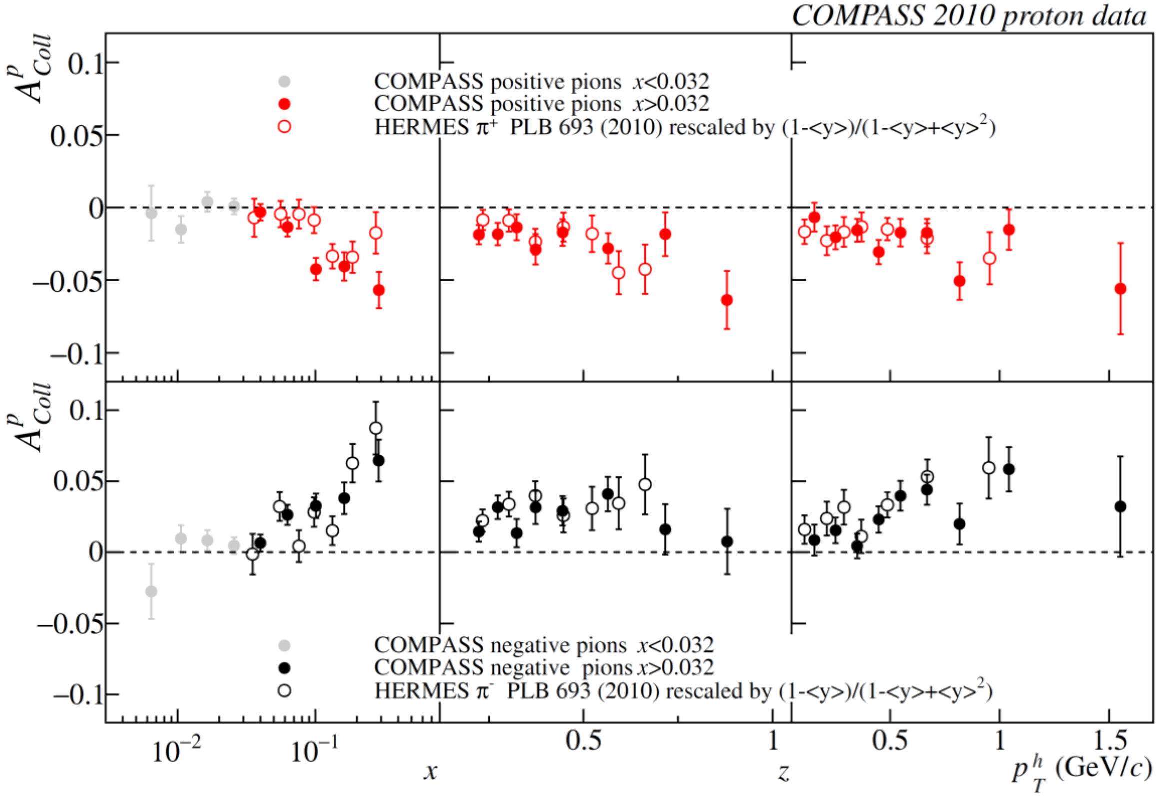


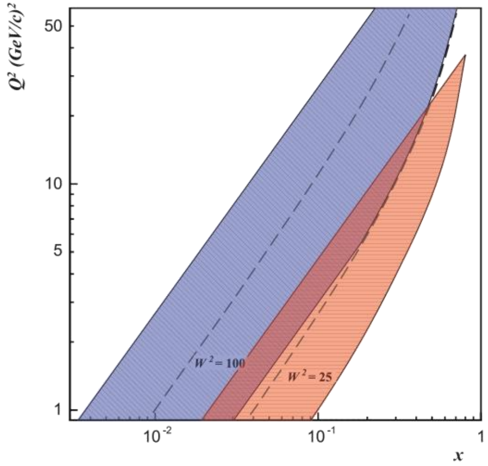
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + \; S_T \,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h + \phi_S\right) + \ldots\right\}$$

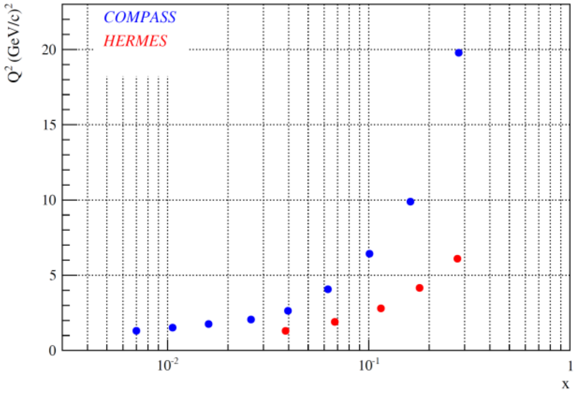
$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES
  (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

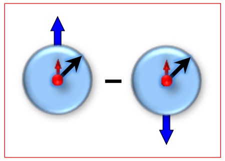
COMPASS PLB 744 (2015) 250







SIDIS TSAs: Collins effect and Transversity

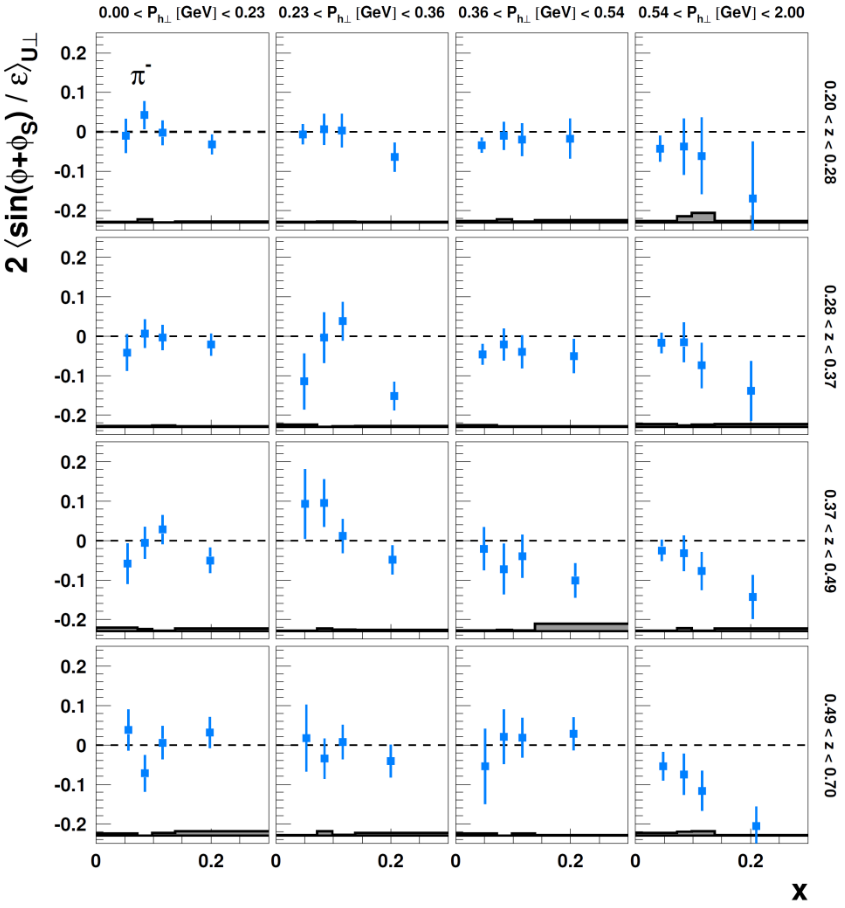


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T \, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h+\phi_S\right) + \ldots\right\}$$

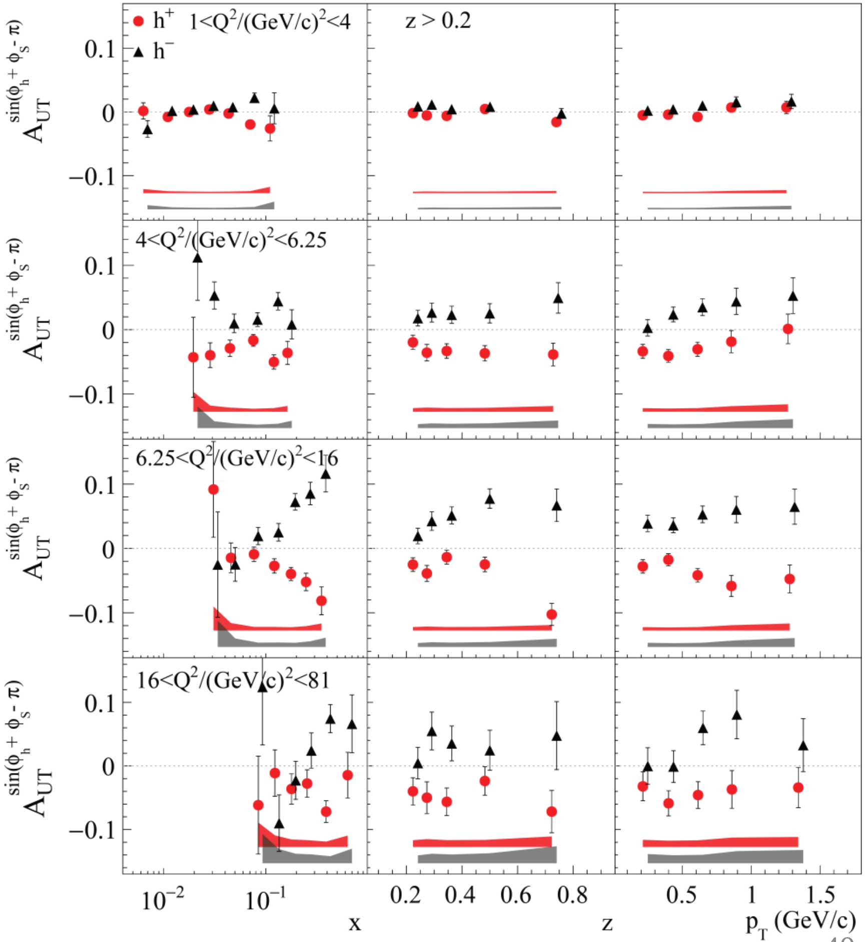
$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES
  (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

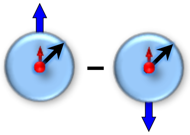
HERMES, JHEP 12 (2020) 010



COMPASS, PBL 770 (2017) 138



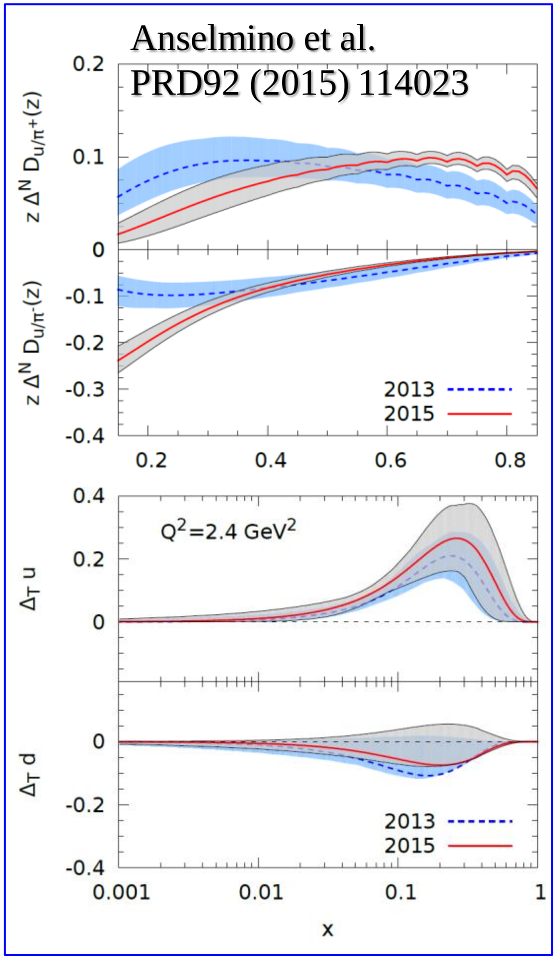
SIDIS TSAs: Collins effect and Transversity



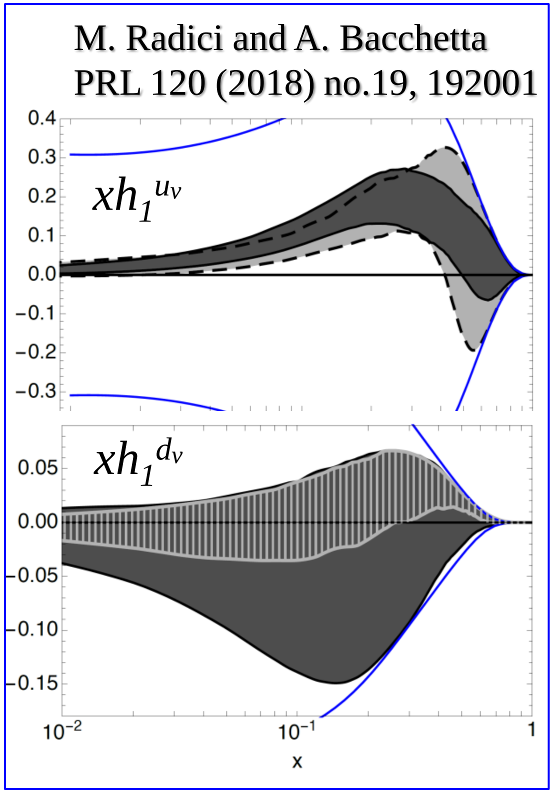
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h+\phi_S\right)+\ldots\ \right\}$$

$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

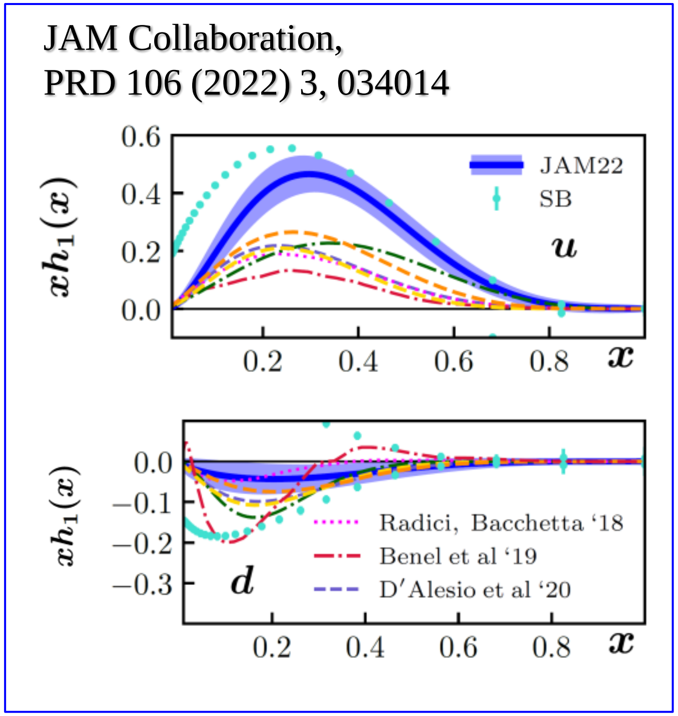
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES
  (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?
- Extensive phenomenological studies and various global fits by different groups



Anselmino et al.
PRD92 (2015) 114023



M. Radici and A. Bacchetta
PRL 120 (2018) no.19, 192001



JAM Collaboration,
PRD 106 (2022) 3, 034014

SIDIS TSAs: Collins effect and Transversity

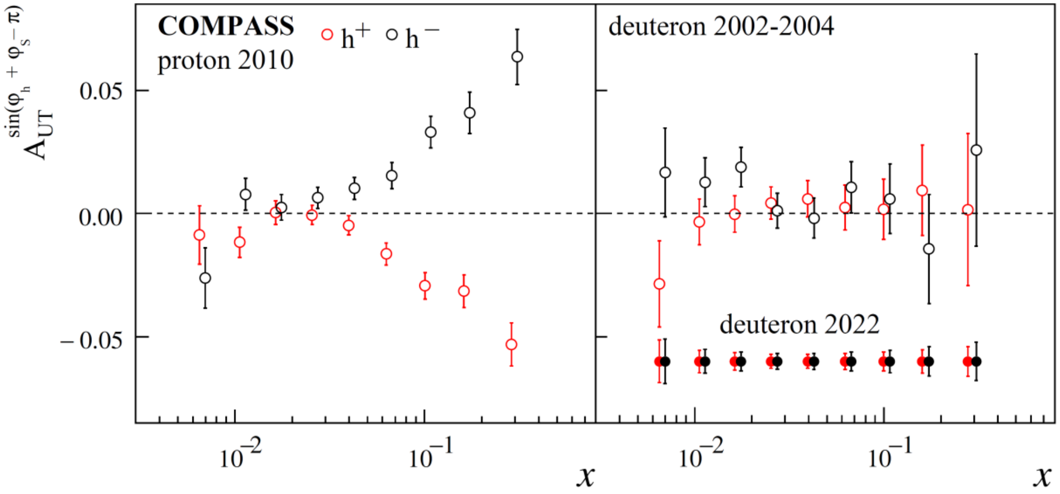
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin\left(\phi_h+\phi_S\right)+\ldots\ \right\}$$

$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

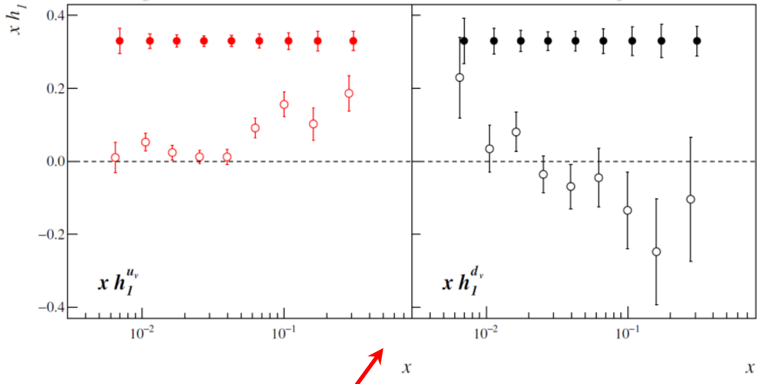
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?
- Extensive phenomenological studies and various global fits by different groups

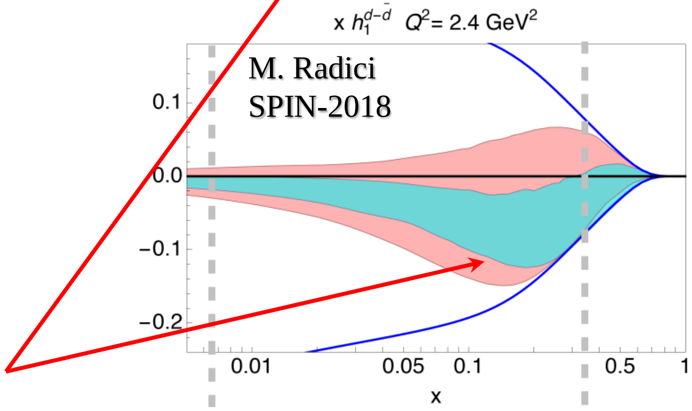
[Addendum to the COMPASS-II Proposal]

Projected uncertainties for Collins asymmetry



Projected uncertainties for transversity PDF



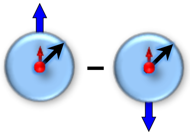


M. Radici
SPIN-2018

COMPASS-II (2022)

- 2nd COMPASS deuteron measurements performed
- Crucial to constrain the transversity TMD PDF for the d-quark

SIDIS TSAs: Collins effect and Transversity

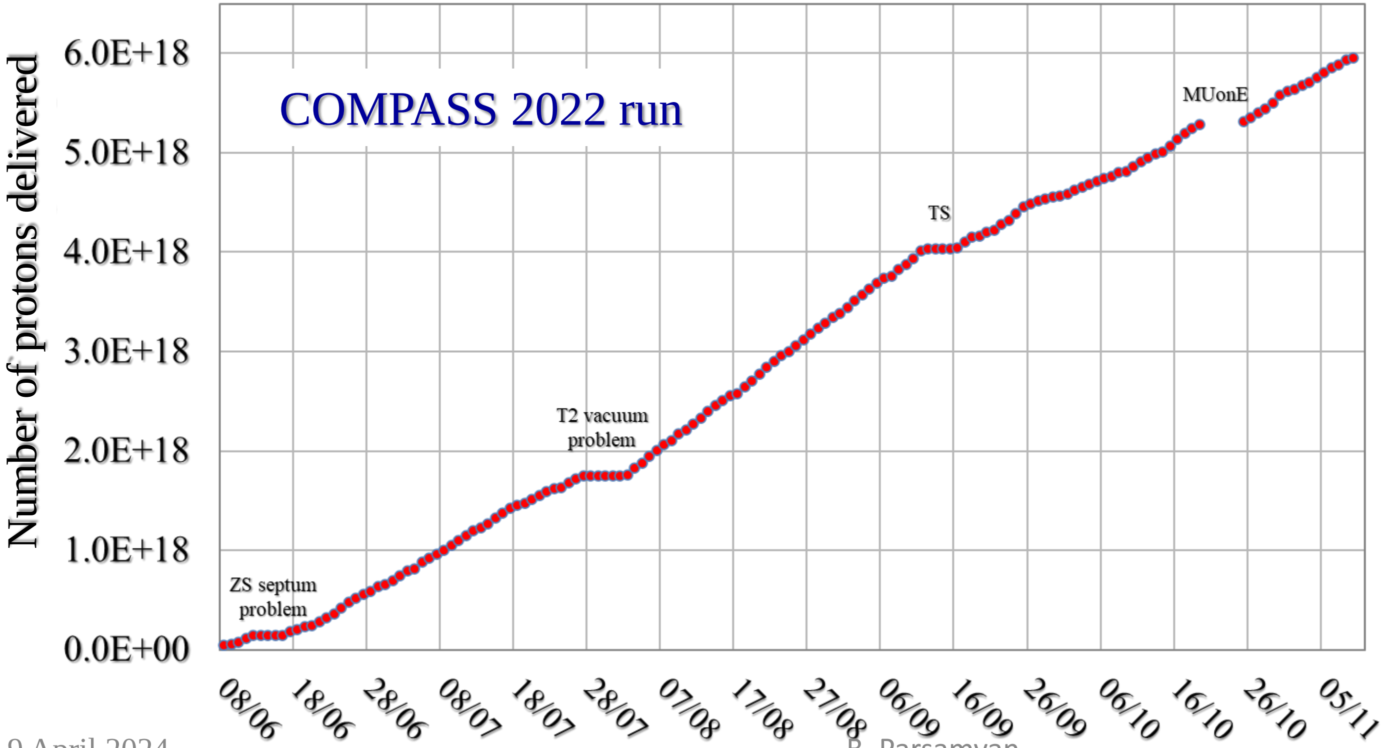


$$\frac{d\sigma}{dx\,dy\,dz\,dp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+ S_T\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\right\}$$

$$F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]$$

- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES
  (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?
- Extensive phenomenological studies and various global fits by different groups

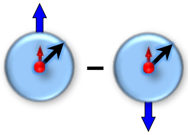
Total protons delivered on the production target: ~5.95×10^{18} (98% of the request) in ~150 days



SPS efficiency: ~ 73%
Spectrometer efficiency: ~ 90%
Physics data collection efficiency: ~ 75%

Highly successful Run in 2022!

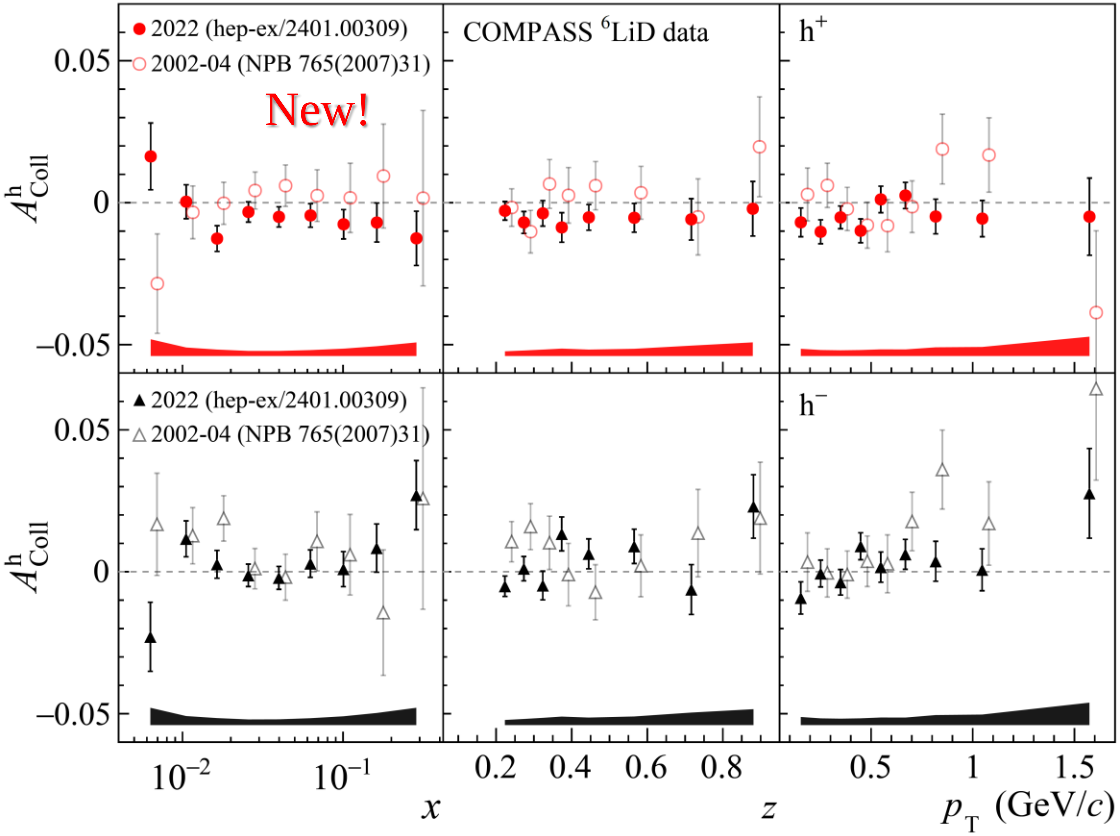
SIDIS TSAs: Collins effect and Transversity



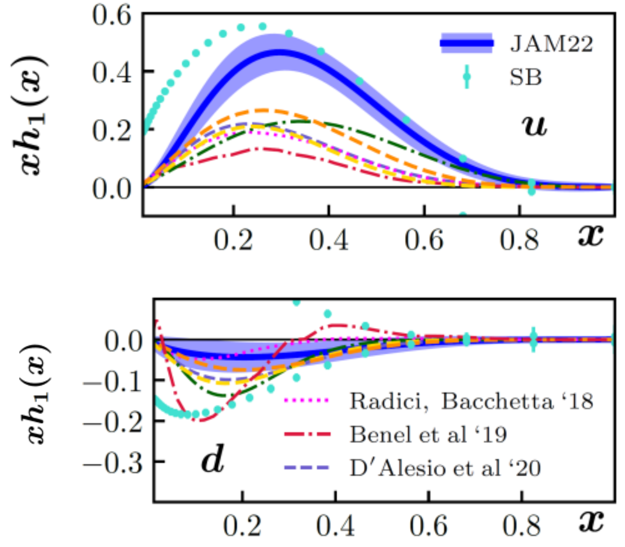
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+\ S_T\ \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)+\ldots\ \right\}$$

$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

- Measured on P/D in SIDIS and dihadron SIDIS
- Extensive phenomenological studies and various global fits by different groups
- New deuteron data crucial to constrain *d*-quark transversity



JAM Collaboration,
PRD 106 (2022) 3, 034014

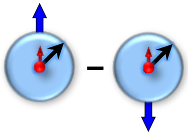


See S. Asatryan's slides

COMPASS 2022 run – highly successful data-taking!

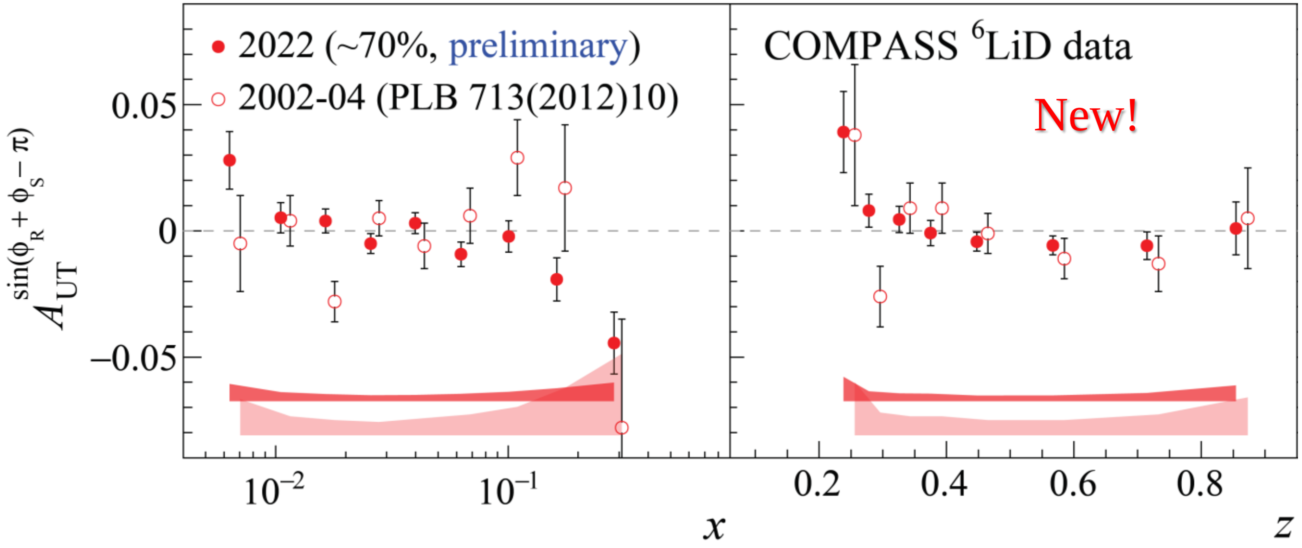
- 2nd COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades

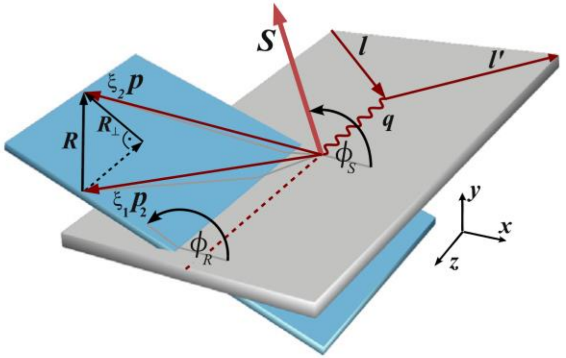
Dihadron Collins effect and Transversity



$$\frac{\mathrm{d}^7\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}M_{\mathrm{hh}}\,\mathrm{d}\phi_{\mathrm{R}}\,\mathrm{d}z\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi_{\mathrm{S}}} = \frac{\alpha^2}{2\pi Q^2 y}\Bigg((1-y+\frac{y^2}{2})\sum_q e_q^2\; f_1^q(x)\; D_{1,q}(z, M_{\mathrm{hh}}^2, \cos\theta) + S_\perp(1-y)\sum_q e_q^2 \frac{|\mathbf{p}_1-\mathbf{p}_2|}{2M_{\mathrm{hh}}}\sin\theta\;\sin\phi_{\mathrm{RS}}\; h_1^q(x)\; H_{1,q}^{\sphericalangle}(z, M_{\mathrm{hh}}^2, \cos\theta)\Bigg)$$

$$A_{\mathrm{UT}}^{\sin\phi_{\mathrm{RS}}} = \frac{|\mathbf{p}_1-\mathbf{p}_2|}{2M_{\mathrm{hh}}}\frac{\sum_q e_q^2\, h_1^q(x)\; H_{1,q}^{\sphericalangle}(z, M_{\mathrm{hh}}^2, \cos\theta)}{\sum_q e_q^2\; f_1^q(x)\; D_{1,q}(z, M_{\mathrm{hh}}^2, \cos\theta)}$$



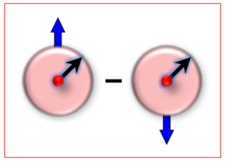


COMPASS 2022 run – highly successful data-taking!

- 2nd COMPASS deuteron measurements conducted in 2022: unique SIDIS data for the next decades
- New results – dihedron Collins-like asymmetries
- Access to collinear transversity PDF; Non-zero trend at large *x*
- Precision comparable with proton results

See S. Asatryan's slides

SIDIS TSAs: Sivers effect

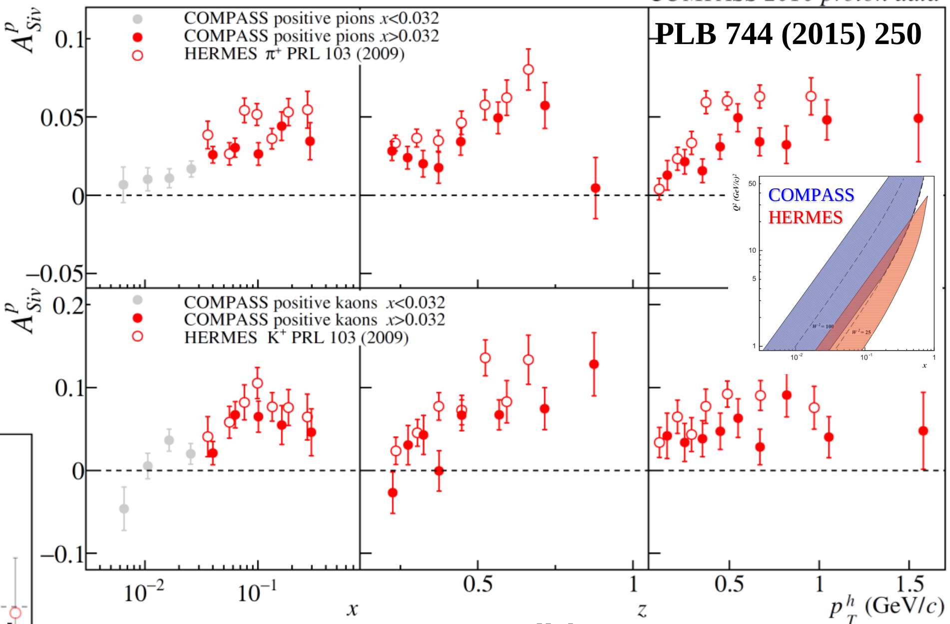


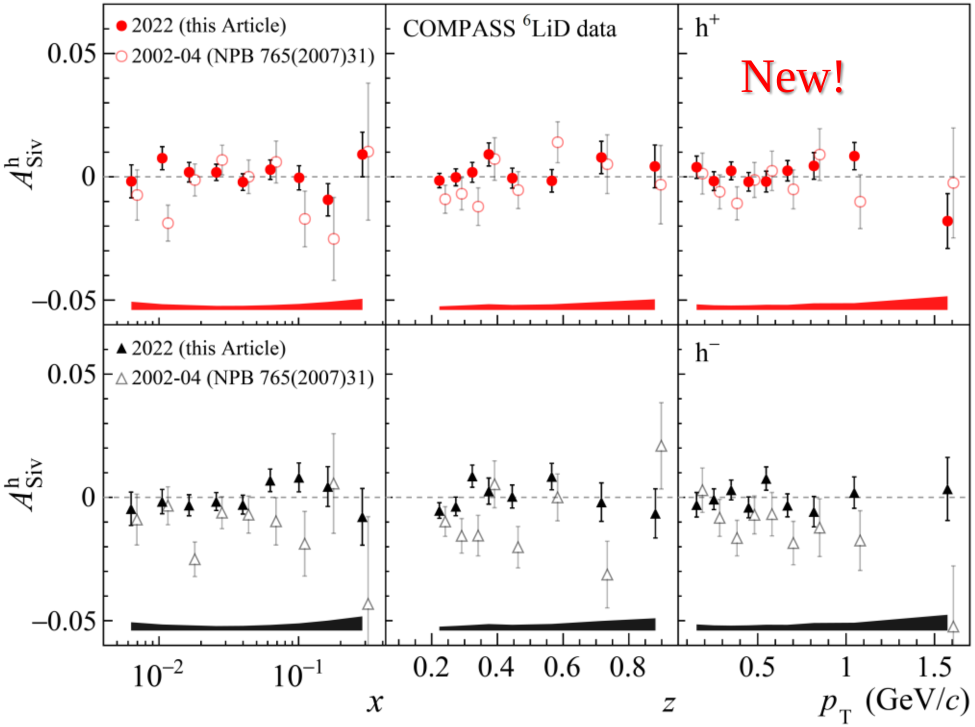
$$\frac{d\sigma}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, A_{UT}^{\sin(\phi_h-\phi_S)} \sin\left(\phi_h - \phi_S\right) + \ldots\right\}$$

$$\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{k}_T}{M} f_{1T}^{\perp q} D_{1q}^h\right], F_{UT,L}^{\sin(\phi_h-\phi_S)} = 0}$$

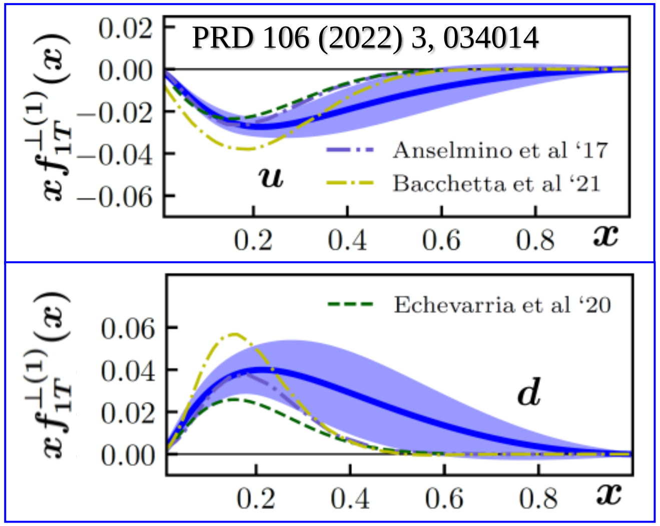
- COMPASS-HERMES discrepancy
- T-oddness: sign-change (SIDIS ↔ Drell-Yan)
  - Explored by COMPASS
- New precise deuteron data from COMPASS
  - Unique input to constrain Sivers PDF

COMPASS 2010 proton data

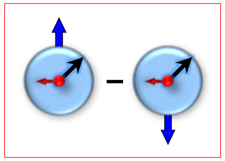




JAM Collaboration



SIDIS TSAs: Kotzinian-Mulders asymmetry

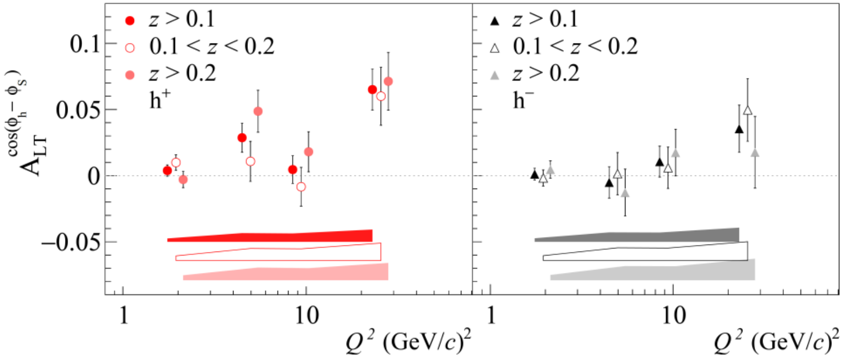


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1+\ldots+ \lambda S_T \sqrt{\left(1-\varepsilon^2\right)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos\left(\phi_h-\phi_S\right)+\ldots\right\}$$

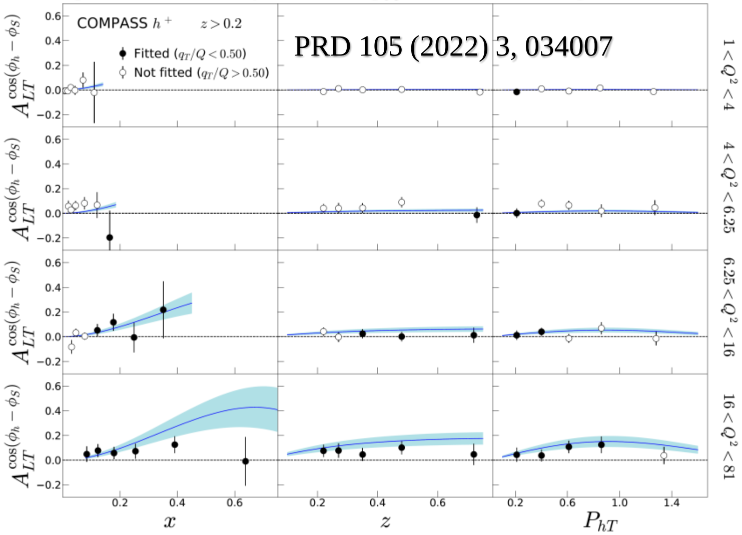
$$\boxed{F_{LT}^{\cos(\phi_h-\phi_S)} = C\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} g_{1T}^q D_{1q}^h\right]}$$

COMPASS/HERMES/CLAS6 results $A_{LT}^{\cos(\phi_h-\phi_S)}$

- Only “twist-2” ingredients
- Sizable non-zero effect for h^+ !
- Similar effect at HERMES

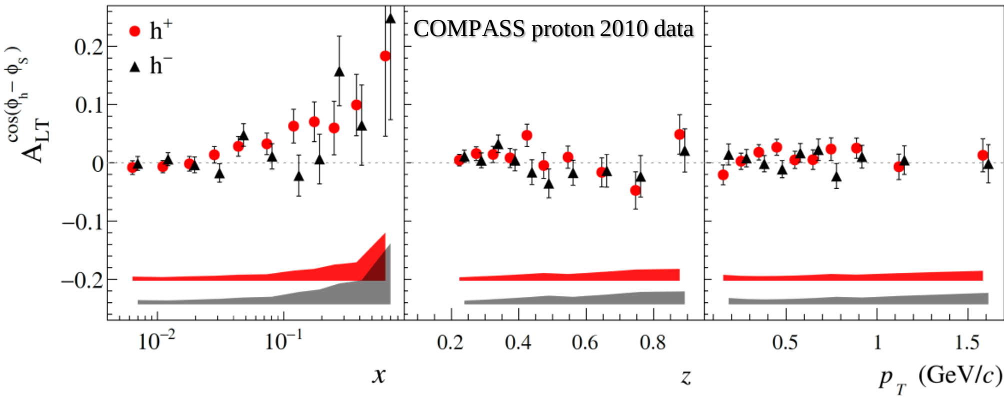


First global QCD analysis of the g_{1T} TMD PDF using SIDIS data

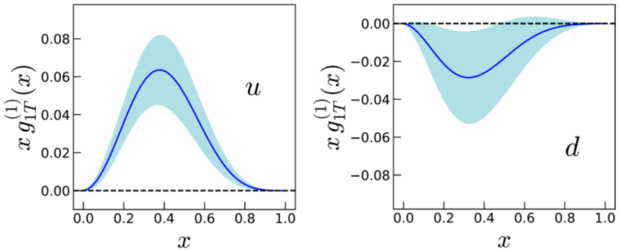


PRD 105 (2022) 3, 034007

COMPASS, PBL 770 (2017) 138; PoS QCDEV2017 (2018) 042



See also, PRD 107, (2023) 034016 – global fit by:
M. Horstmann, A. Schafer and A. Vladimirov



COMPASS 2022 run: new unique deuteron data

COMPASS 25 years 1997 - 2022

Pavia group fits

hermes proton [H] 95 data points
*Airapetian et al., P.R.L. **103** (09) 152002*

Jefferson Lab neutron [³He] 6 data points
*Qian et al., P.R.L. **107** (11) 072003*

COMPASS 2009 deuteron [⁶LiD] 88 data points
*Alekseev et al., P.L. **B673** (09) 127*

COMPASS 2017 Proton [NH₃] 111 data points
*Adolph et al., P.L. **B770** (17) 138*

Bacchetta, Delcarro, Pisano, Radici, in preparation

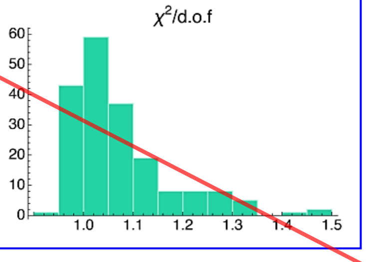
analysis of statistical error with replica method (200)
68% confidence level

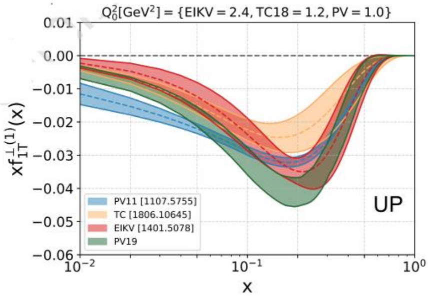
Same kinematic cuts applied to unpolarized

$Q^2 \geq 1.4$ GeV² $\quad 0.2 \leq z \leq 0.7$
$P_{hT} < \min[0.2Q, 0.7Qz] + 0.5$ GeV

x, z, P_{hT} data projections

300 data points → **118** data fitted
14 free parameters
χ²/d.o.f. = 1.06 ± 0.10

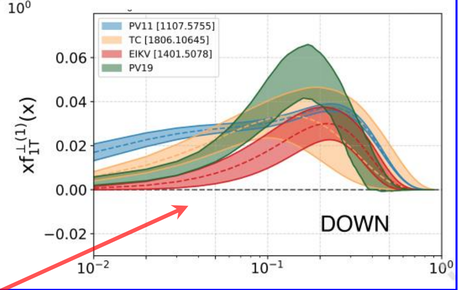




PV11	*Bacchetta & Radici, P.R.L. **107** (11)*
EIKV	*Echevarria et al., P.R. **D89** (14)*
TC	*Boglione et al., JHEP **1807** (18)*
PV19	*Bacchetta, Delcarro, Pisano, Radici, in preparation*

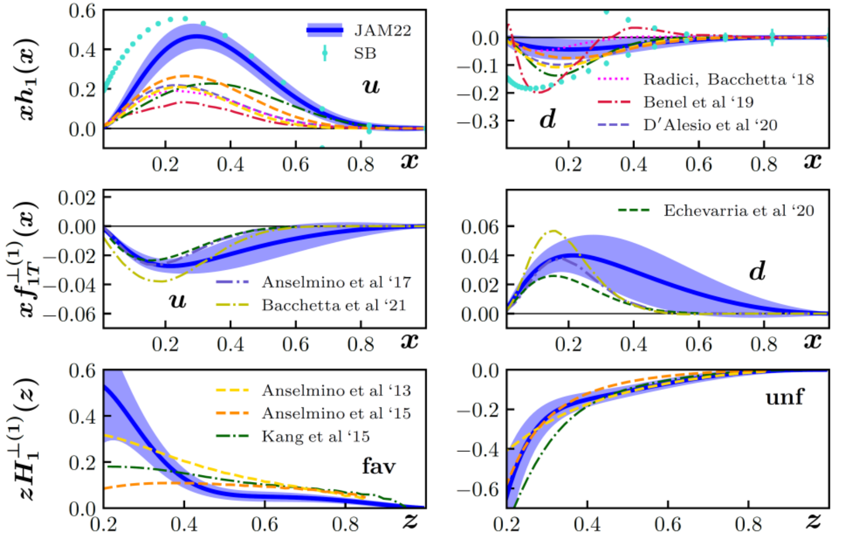
$$f_{1T}^{\perp(1)}(x) = \int d\mathbf{k}_T \, \frac{\mathbf{k}_T^2}{2M^2} \, f_{1T}^{\perp}(x, \mathbf{k}_T)$$

SEA 10^{-2} × smaller
(compatible with 0)

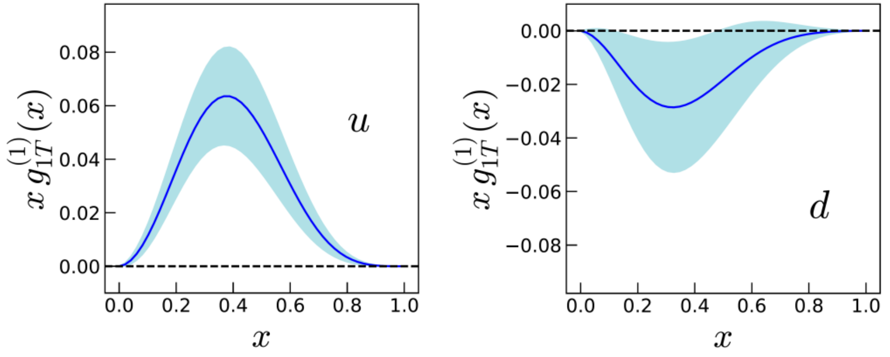


COMPASS 2022 deuteron run

JAM Collaboration, PRD 106 (2022) 3, 034014



S. Bhattacharya, Z. B. Kang, A. Metz, G. Penn and D.Pitonyak
PRD 105 (2022) 3, 034007



SIDIS and single-polarized DY x-sections at twist-2 (LO)

SIDIS

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)$$

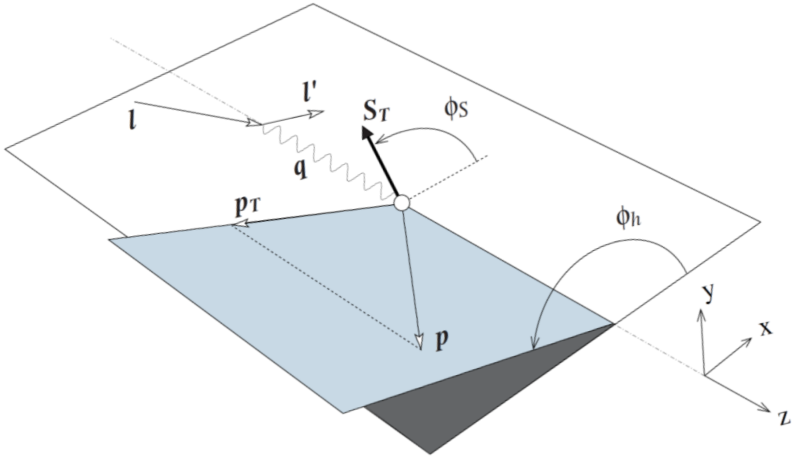
$$\times \left\{ \begin{array}{l} 1+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h \\ + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h + S_L\lambda\sqrt{1-\varepsilon^2}\,A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S)\end{array}\right] \\ + S_T\lambda\left[\sqrt{(1-\varepsilon^2)}\,A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S)\right]\end{array}\right\}$$

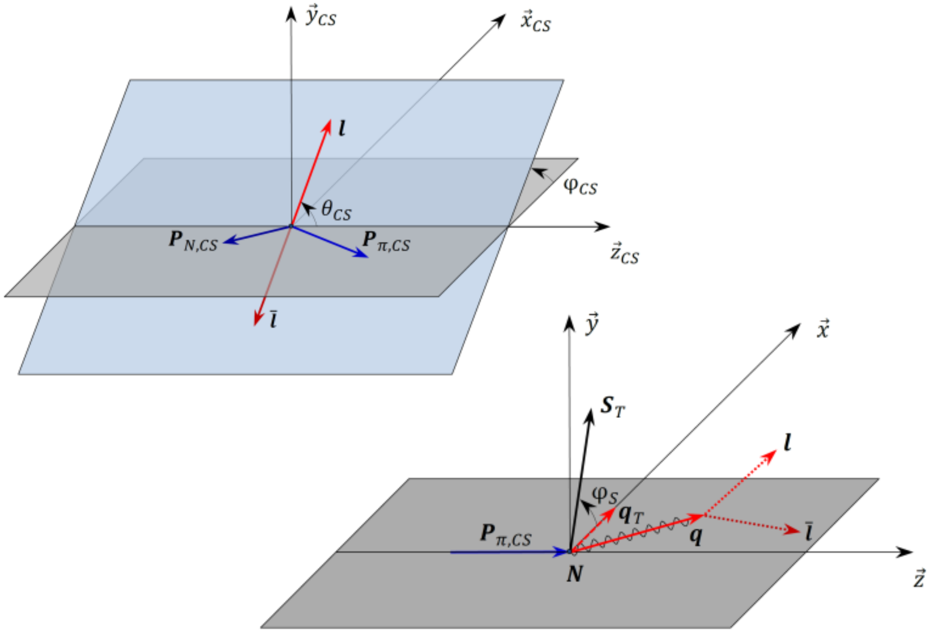
DY

$$\frac{d\sigma^{LO}}{dq^4 d\Omega}\propto F_U^1\left(1+\cos^2\theta_{CS}\right)$$

$$\times \left\{ \begin{array}{l} 1+D_{\left[\sin^2\theta_{CS}\right]}A_U^{\cos 2\varphi_{CS}}\cos 2\varphi_{CS} \\ + S_L\sin^2\theta_{CS}A_L^{\sin 2\varphi_{CS}}\sin 2\varphi_{CS} \\ + S_T\left[\begin{array}{l} A_T^{\sin\varphi_S}\sin\varphi_S \\ +D_{\left[\sin^2\theta_{CS}\right]}\left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)}\sin(2\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)}\sin(2\varphi_{CS}+\varphi_S)\end{array}\right)\end{array}\right]\end{array}\right\}$$

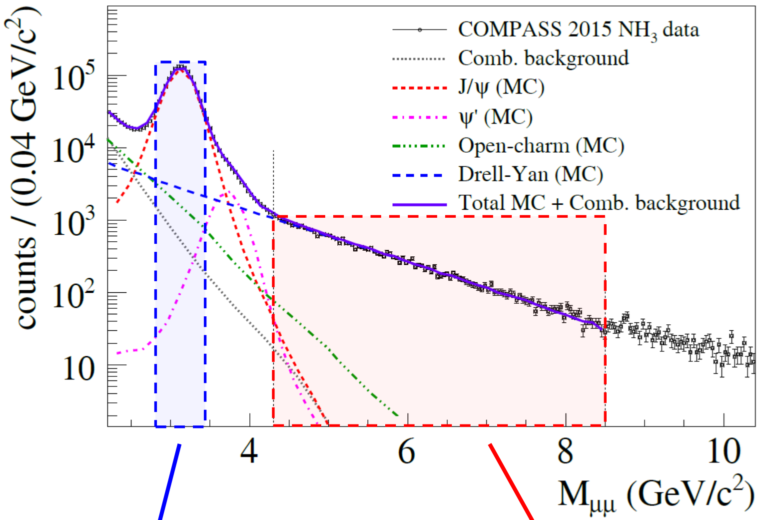
where $D_{\left[\sin^2\theta_{CS}\right]}=\sin^2\theta_{CS}/\left(1+\cos^2\theta_{CS}\right)$

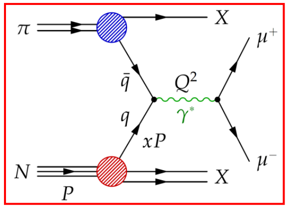




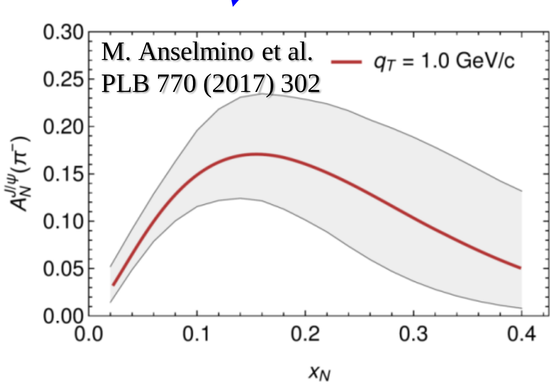
See M. Niemiec’s talk

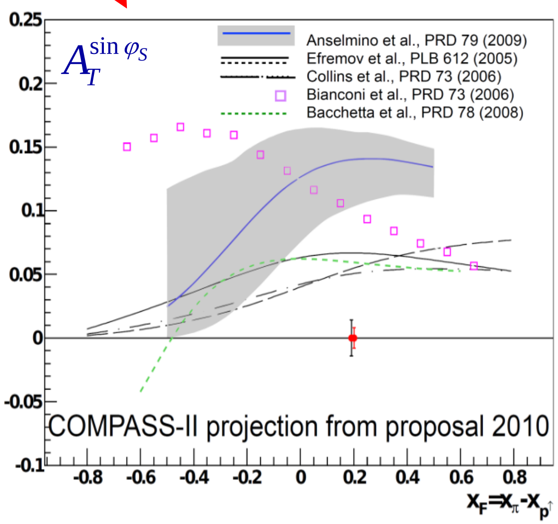
Single-polarized Drell-Yan cross-section at twist-2 (LO)





$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ \begin{aligned} &1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ &+ S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ &+ S_T \left[\begin{aligned} &A_T^{\sin\varphi_S} \sin\varphi_S \\ &+ D_{[\sin^2\theta_{CS}]} \left(\begin{aligned} &A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\ &+ A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{aligned} \right) \end{aligned} \right] \end{aligned} \right\}$$





$A_U^{\cos 2\varphi_{CS}} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1,p}^{\perp q}}$	Boer-Mulders (T-odd)
$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes \underline{f_{1T,p}^{\perp q}}$	Sivers (T-odd)
$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1,p}^{q}}$	Transversity
$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto \underline{h_{1,\pi}^{\perp q}} \otimes \underline{h_{1T,p}^{\perp q}}$	Pretzelosity

SIDIS ↔ Drell-Yan sign-change of the T-odd TMD PDFs

COMPASS phase-II proposal submitted in 2010 (Drell-Yan, DVCS,…)

Predictions for a large Sivers effect in Drell-Yan and J/ψ at COMPASS → sign change test

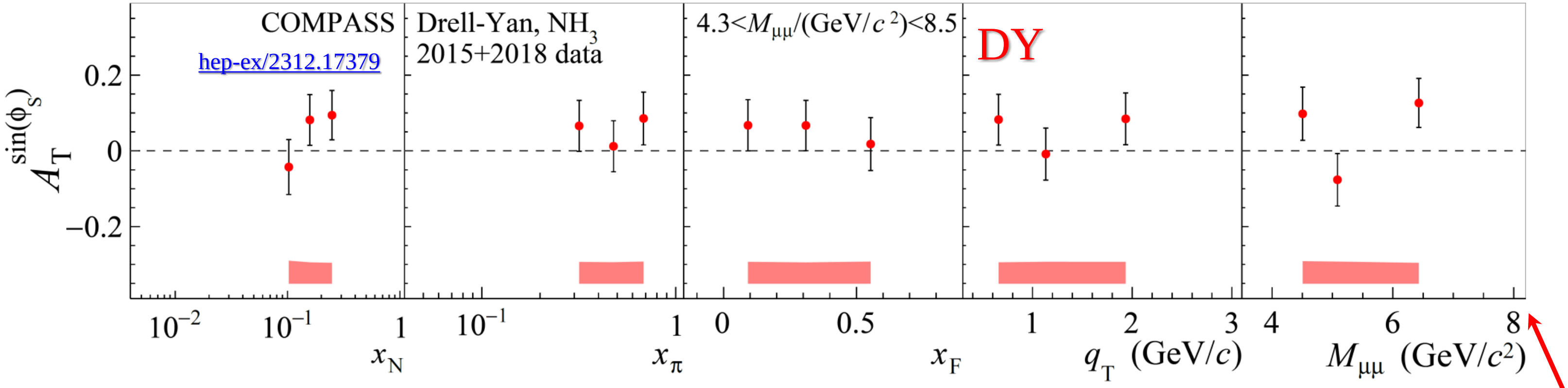
Drell-Yan TSAs – Sivers effect

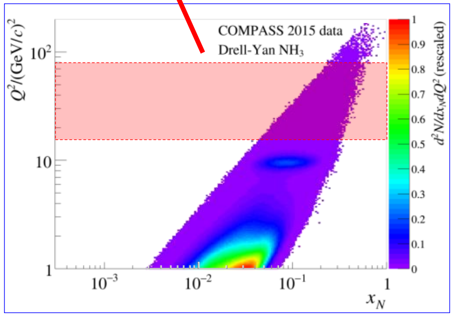
$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T\left[A_T^{\sin\varphi_S}\sin\varphi_S + \ldots\right]$$

Sivers DY TSA

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

See M. Niemiec's talk



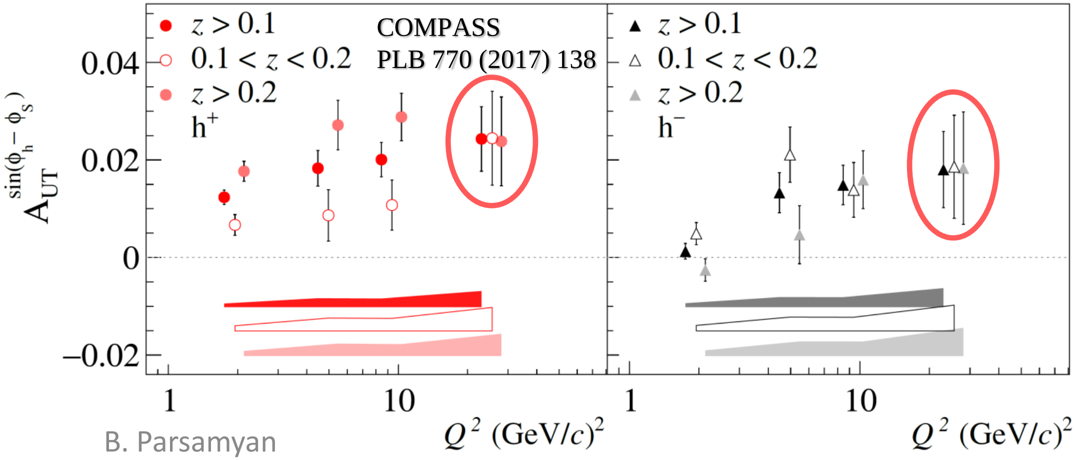


Sivers SIDIS TSA

$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$$

COMPASS proton Sivers measurements

- Clear signal in the matching Q^2 ranges



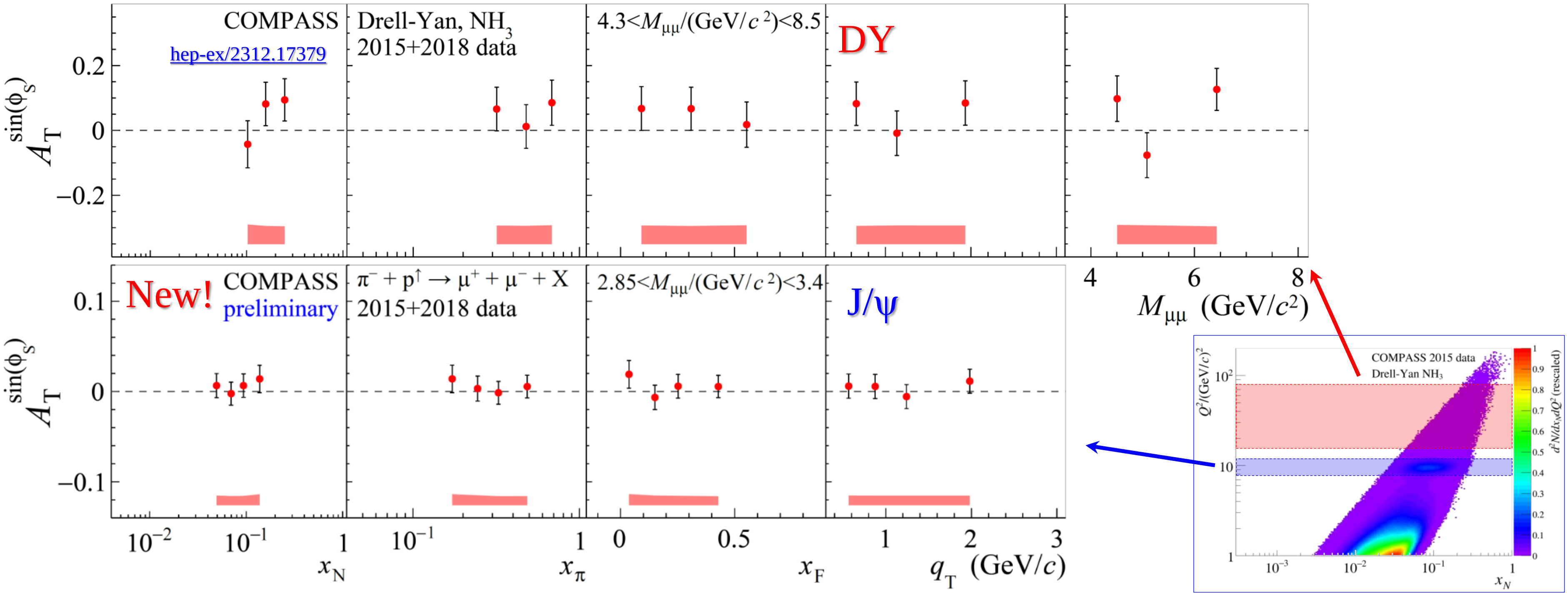
Drell-Yan TSAs – Sivers effect

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + \mathrm{S_T}\left[A_T^{\sin\varphi_S} \sin\varphi_S + \ldots \right]$$

Sivers DY TSA

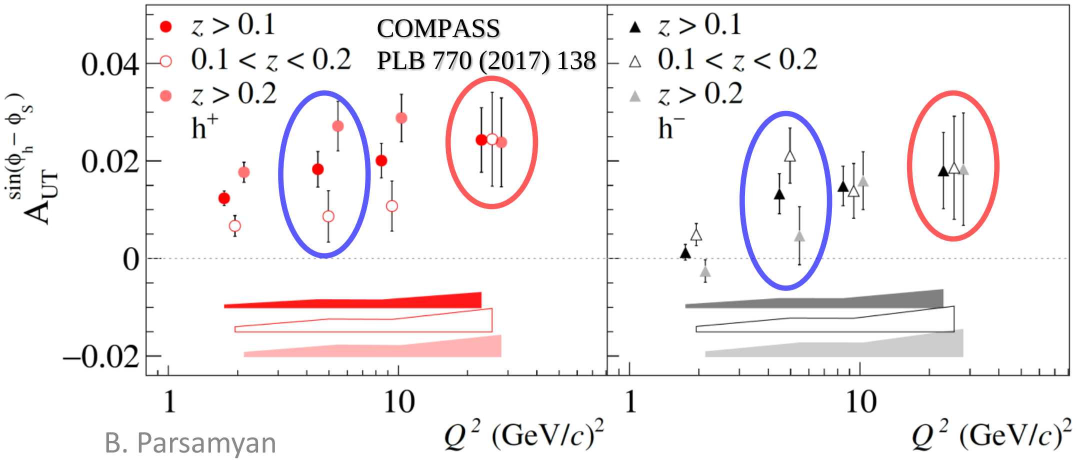
$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,\mathrm{p}}^{\perp q}$$

See M. Niemiec's talk



Sivers SIDIS TSA

$$A_{UT}^{\sin(\phi_h - \phi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^{h}$$



COMPASS proton Sivers measurements

- Clear signal in the matching Q^2 ranges

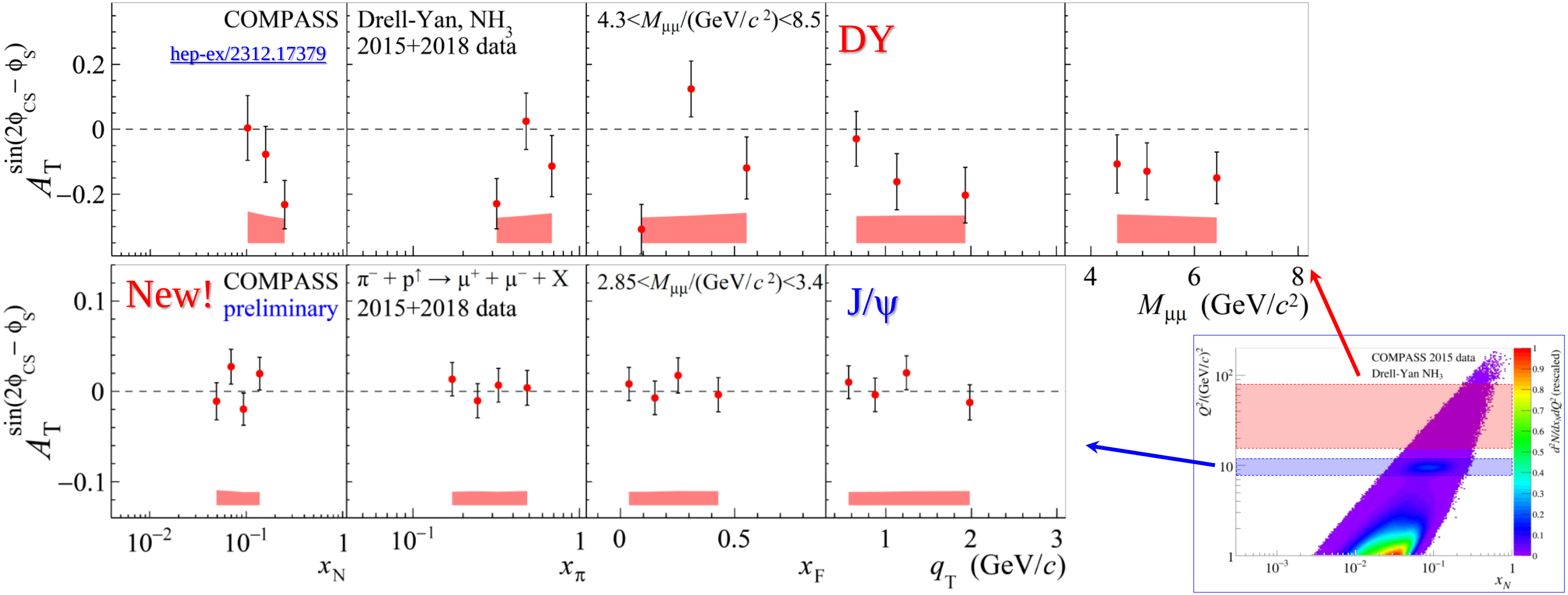
Drell-Yan TSAs – Transversity

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1+\ldots+ S_T\left[D_{\left[\sin^2\theta_{CS}\right]} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin\left(2\varphi_{CS}-\varphi_S\right)+\ldots\right]$$

Transversity DY TSA

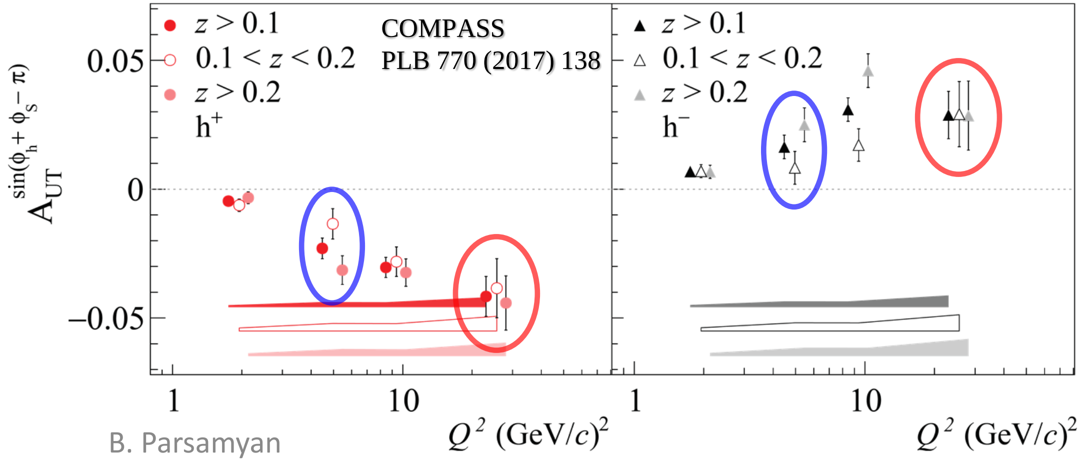
$$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,\mathrm{p}}^{q}$$

See M. Niemiec's talk



Collins SIDIS TSA

$$A_{UT}^{\sin(\phi_h+\phi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$



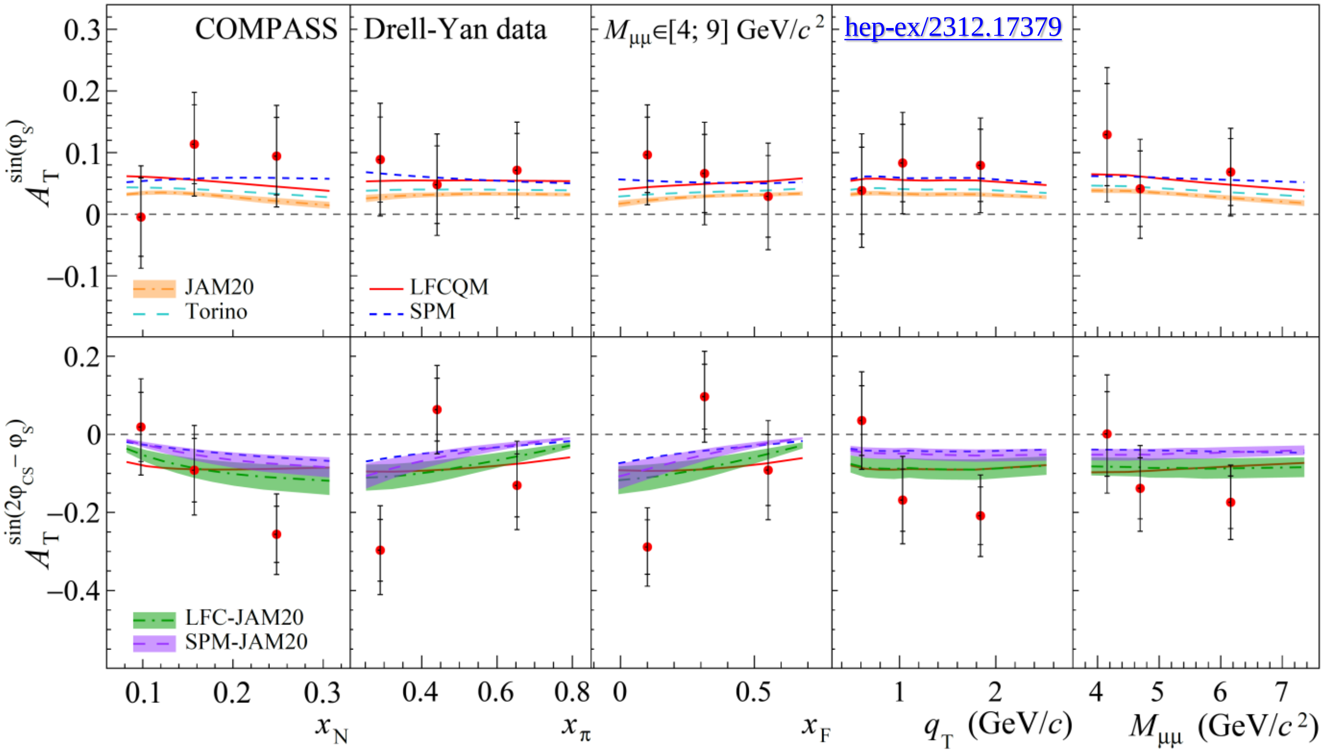
COMPASS proton Collins measurements

- Clear signal in the matching Q^2 ranges

Transverse-spin asymmetries in $\pi^- p^\uparrow$ scattering

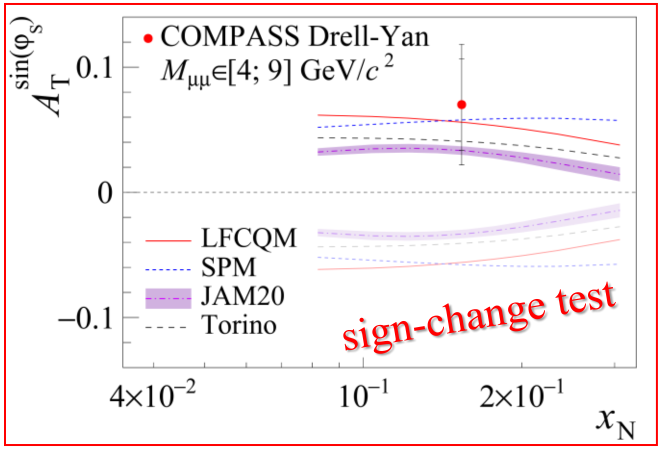
Theory curves based on S. Bastami et al. JHEP 02, (2021),166

See M. Niemiec's talk

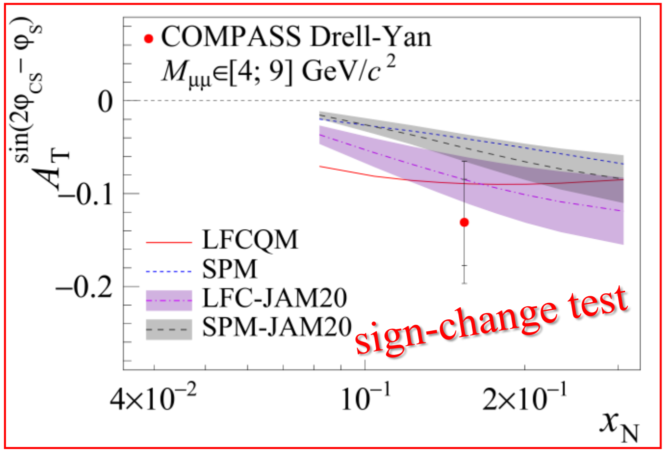


Drell-Yan measurements

- Ruled out predictions for large asymmetries
- General agreement with currently available model calculations
- COMPASS data favors the sign-change hypothesis for the Sivers TMD PDF
- COMPASS data also favors pion Boer-Mulders TMD PDF sign-change (model-based)



sign-change test



sign-change test

J/ψ production channel

- All TSAs are small and compatible with zero
- Hint that J/ψ production might go via gluon-gluon fusion in COMPASS
- Access to small gluon TMDs?

Conclusions

- Importance of careful understanding and confrontation of experimental data from different experiments
  - Different kinematic domains and phase-space limitations
  - Experiments employ complex analysis techniques, Monte-Carlo simulations, and sophisticated corrections (acceptance, VMs, radiative corrections)
- Close collaboration between different experiments → general benefit for the field
  - Knowledge transfer, comparison of the analysis techniques, tools, and methodology, cross-analyses between different experiments
- Close collaboration between experiment and phenomenology/theory
  - Flexibility in adapting on the analysis side to the choice of the observables, phase-space selections, etc. (before publishing the data)
  - Different possibilities for common paper projects, external membership
- Possibility to organize effective and fruitful collaborative work

Conclusions

- COMPASS holds the record for the longest-running CERN experiment (20 years of data-taking)
- Series of successful and important measurements addressing nucleon spin-structure
  - Inclusive measurements, unpolarized and polarized SIDIS (longitudinal/transverse)
  - First-ever polarized Drell-Yan measurements
- A wealth of (SI)DIS, Drell-Yan, DVCS, HEMP data collected across the years
  - Petabytes of data available for analysis
- Wide and unique kinematic domain accessing low x and large Q^2
  - Will remain unique for at least another decade
- World-unique SIDIS deuteron data collected in 2022
  - Highly successful run, promising preliminary results
- Since 2023 the experiment entered the Analysis Phase
  - The spectrometer has been transferred to the COMPASS successor in the M2 beamline – the AMBER collaboration
  - 3 new groups joined COMPASS in the course of 2023 for the Analysis Phase
  - If you are interested – don’t hesitate to get in touch!

Thank You!

2024
30/09 - 04/10

Joint XX-th International Workshop on Hadron Structure and Spectroscopy and 5-th Workshop on Correlations in Partonic and Hadronic Interactions

COMPASS
25 years
1997 - 2022

IWHSS

CPHI

Yerevan
Armenia

Yerevan, Armenia

30 September – 4 October, 2024

https://indico.cern.ch/e/IWHSS-CPHI-2024

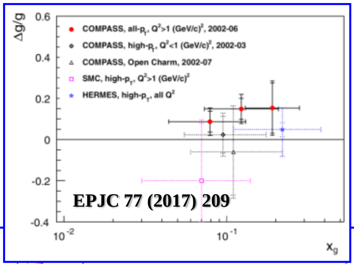
- Spare slides

COMPASS data taking campaigns

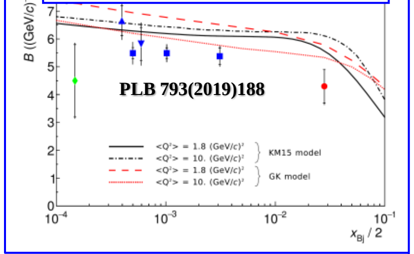
Beam	Target	year	Physics programme
μ^+	Polarized deuteron (^{6}LiD)	2002 2003 2004	80% Longitudinal | 20% Transverse SIDIS
		2006	Longitudinal SIDIS
	Polarized proton (NH_3)	2007	50% Longitudinal | 50% Transverse SIDIS
π | K | p	LH_2, Ni, Pb, W	2008 2009	Spectroscopy
μ^+	Polarized proton (NH_3)	2010	Transverse SIDIS
		2011	Longitudinal SIDIS
π | K | p	Ni	2012	Primakoff
$\mu^\pm$	LH_2	2012	Pilot DVCS & HEMP & unpolarized SIDIS
π^-	Polarized proton (NH_3)	2014	Pilot Drell-Yan
		2015 2018	Transverse Drell-Yan
$\mu^\pm$	LH_2	2016 2017	DVCS & HEMP & unpolarized SIDIS
μ^+	Polarized deuteron (^{6}LiD)	2021 2022	Transverse SIDIS

COMPASS Legacy

COMPASS
25 years
1997 - 2022



EPJC 77 (2017) 209



PLB 793(2019)188

NEWS

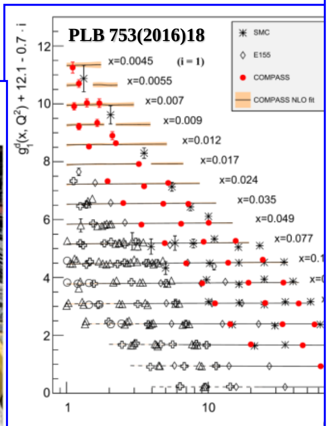
COMPASS measures the pion polarizability

23 February 2015

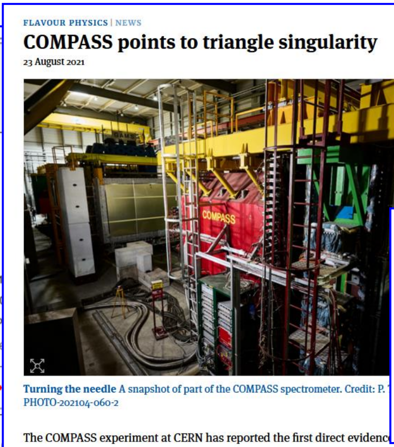
CERN experiment brings precision to a cornerstone of particle physics

11 FEBRUARY, 2015

The COMPASS experiment in the North Area on the Prévessin site at CERN studies hadron structure both with pion beams and with muon beams – a powerful combination. Image credit: CERN-EX-1105182-01.



PLB 753(2016)18



FLAVOUR PHYSICS | NEWS

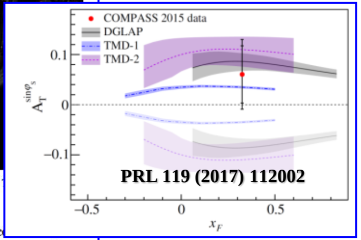
COMPASS points to triangle singularity

23 August 2021

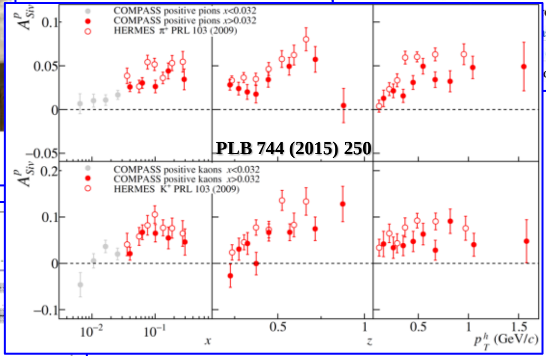
CERN COURIER

Turning the needle A snapshot of part of the COMPASS spectrometer. Credit: P.
PHOTO-202104-060-2

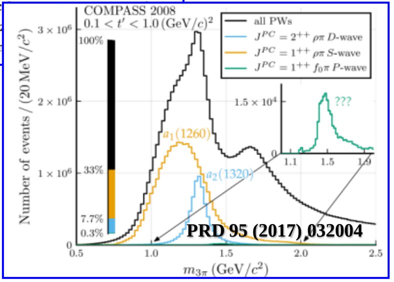
The COMPASS experiment at CERN has reported the first direct evidenc
on decays which can masquerade as a resonance.
st week in Physic
collaboration in
called triangle sin



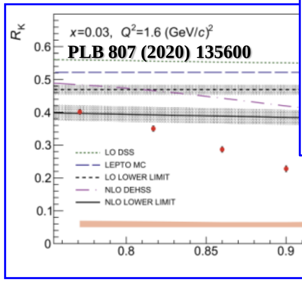
PRL 119 (2017) 112002



PLB 744 (2015) 250

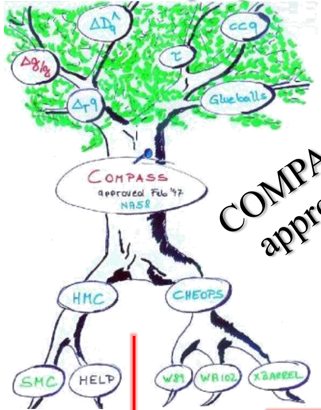


PRD 95 (2017) 032004

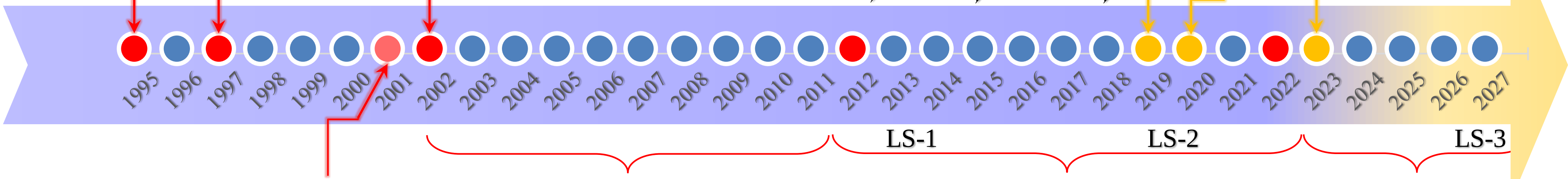


PLB 807 (2020) 135600

COMPASS proposal



AMBER
Apparatus for Meson and Baryon Experimental Research



COMPASS approval

COMPASS 1st data taking

SIDIS L/T

Spectroscopy

SIDIS L/T

Primakoff

DVCS (pilot)

Drell-Yan

DVCS

Drell-Yan

COMPASS++/AMBER proposal

AMBER approval

SIDIS T

AMBER 1st data taking

Pilot run

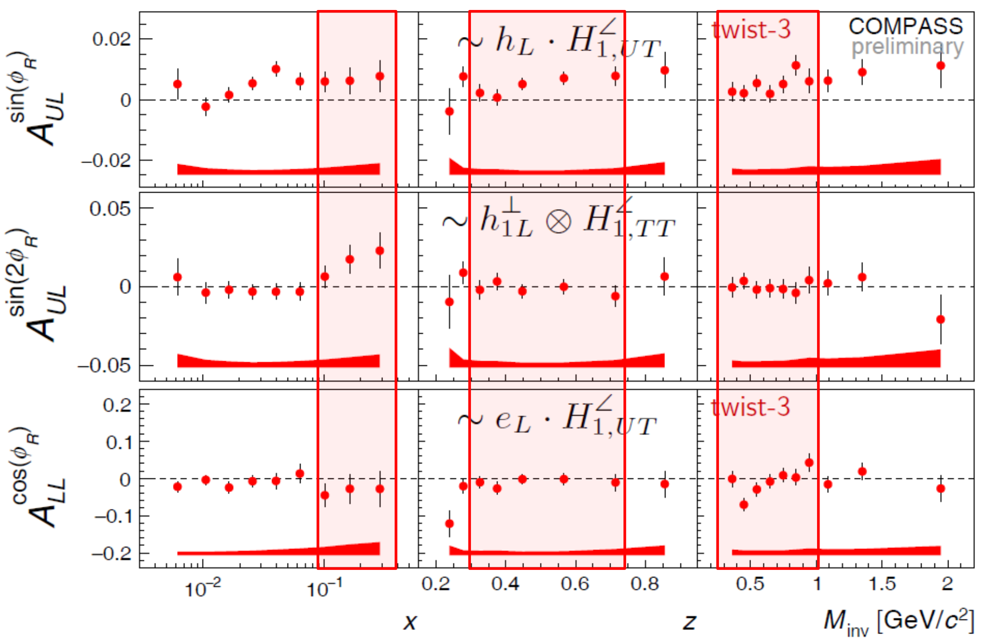
Phase I

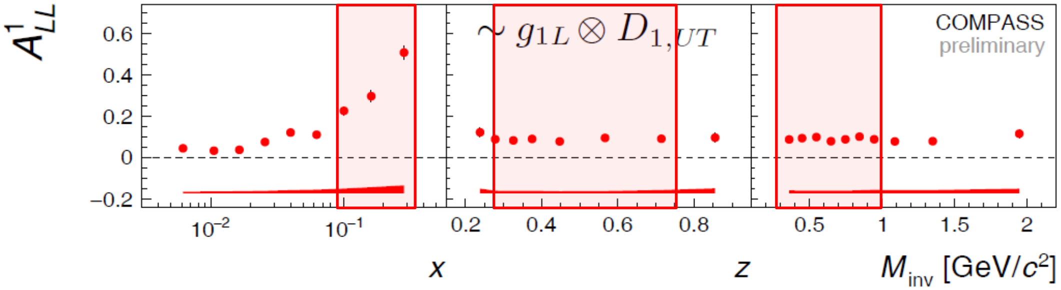
Phase II

Analysis Phase

Selected results for di-hadron LSAs

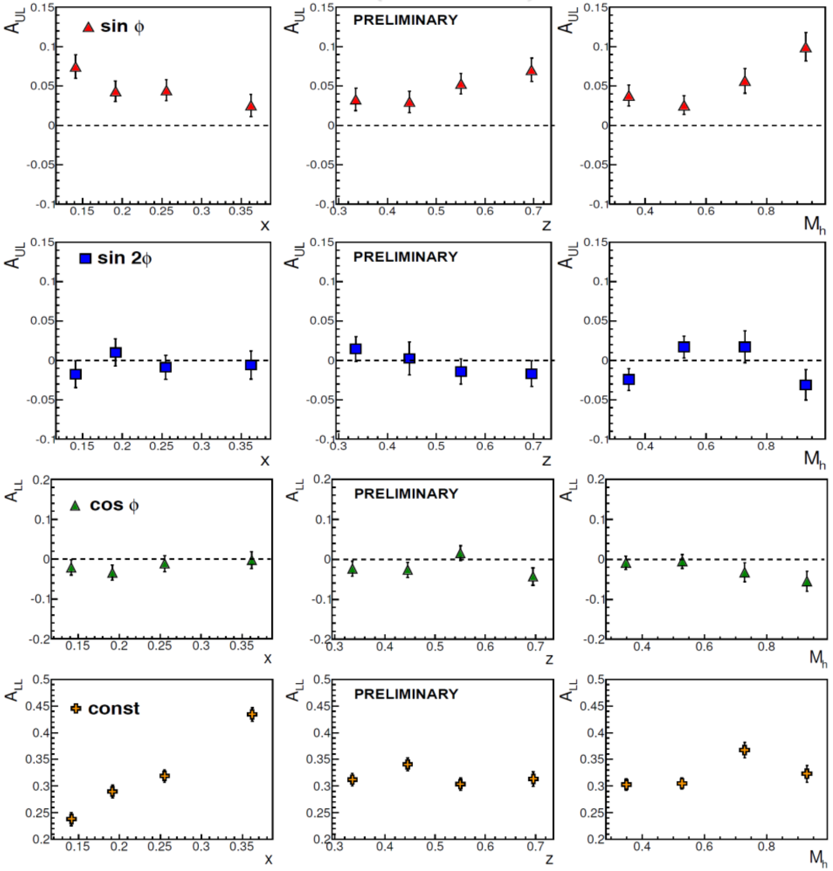
COMPASS (NH$_3$) 2007+2011 data: preliminary



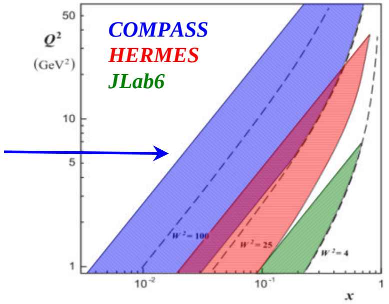


CLAS 6 GeV (NH$_3$)

S. A. Pereira: PoS (DIS 2014) 231



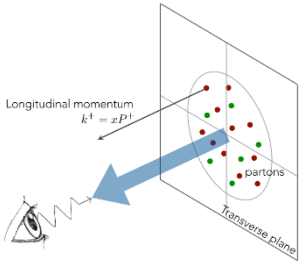
$Q^2 > 1\,(\mathrm{GeV}/c)^2$
$0.0025 < x < 0.7$
$0.1 < y < 0.9$
$W > 5\,\mathrm{GeV}/c^2$

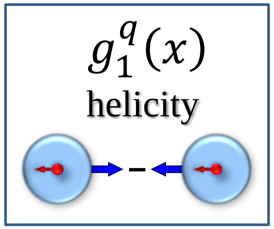


- Alternative way to access various twist-2/-3 distributions
- Non zero signal for $A_{UL}^{\sin\phi_R}$ and A_{LL}^{1}
- CLAS-COMPASS: different behavior for $A_{UL}^{\sin 2\phi_R}$ at large x?

Nucleon spin structure: helicity $g_{1,d(p)}^{q}(x)$

COMPASS
25 years
1997 - 2022



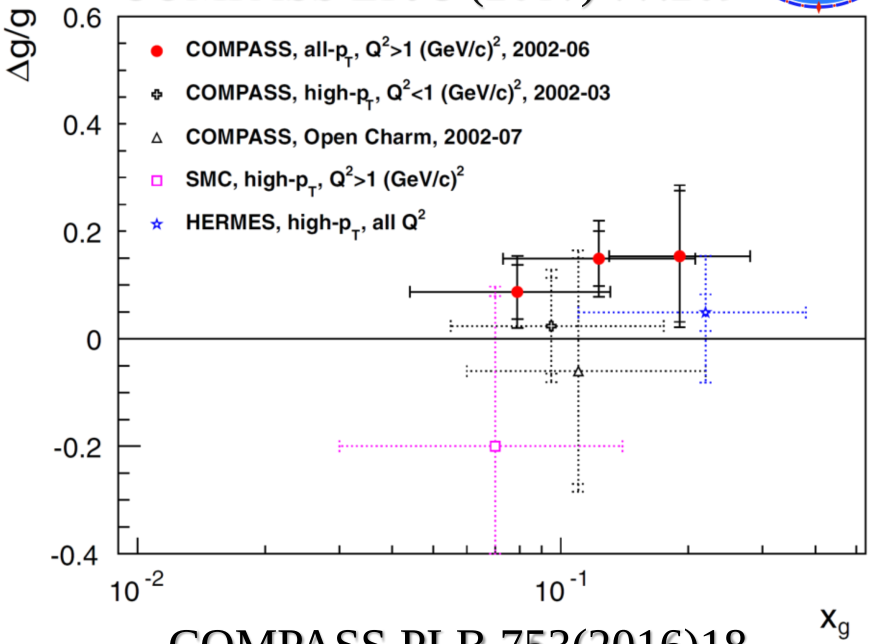


$g_1^q(x)$

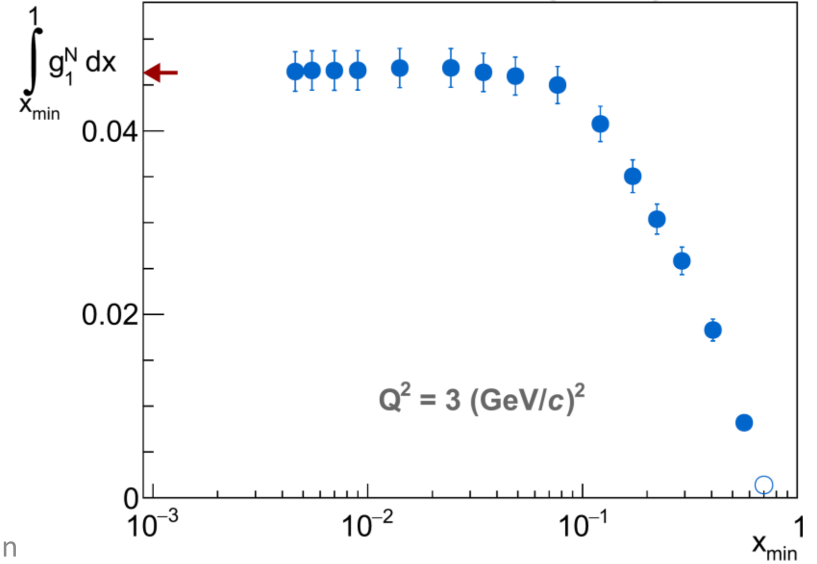
helicity

- COMPASS contribution:
  lowest x and highest Q^2 regions
- Both deuteron and proton target data
- For the first time non-zero spin effects at smallest x and Q^2 – positive signal for $g_1{}^p(x)$
- Gluon polarization measurements
  via open charm and SIDIS
- COMPASS - first to rule out a large gluon polarization in the nucleon!
  Precise test of Bjorken sum rule (9% level)

COMPASS EPJC (2017) 77:209



COMPASS PLB 753(2016)18



SIDIS TSAs: Collins and Sivers effects (proton)

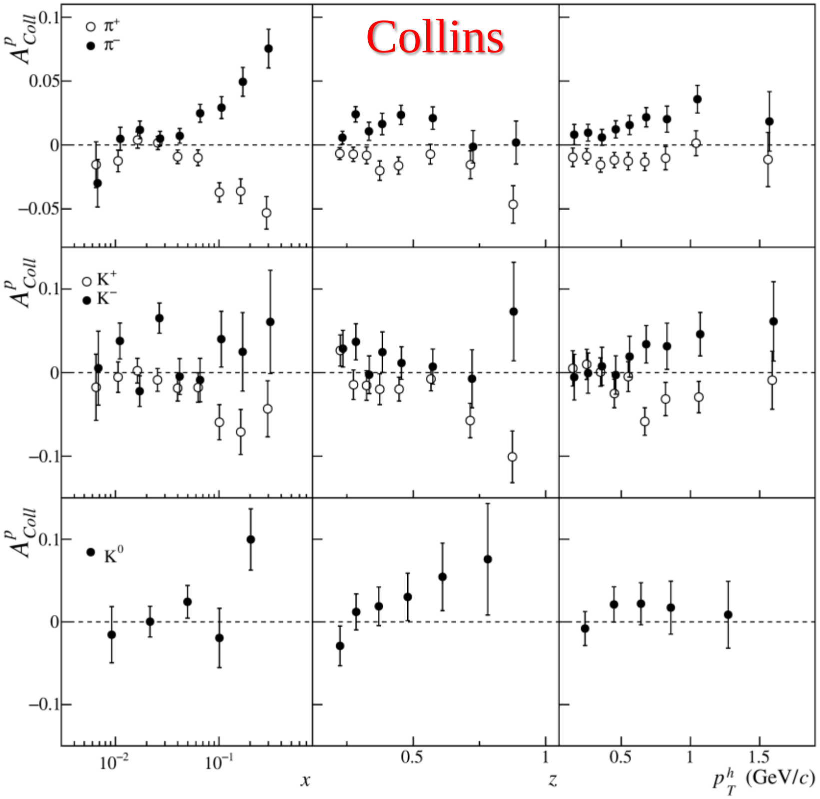
COMPASS
25 years
1997 - 2022

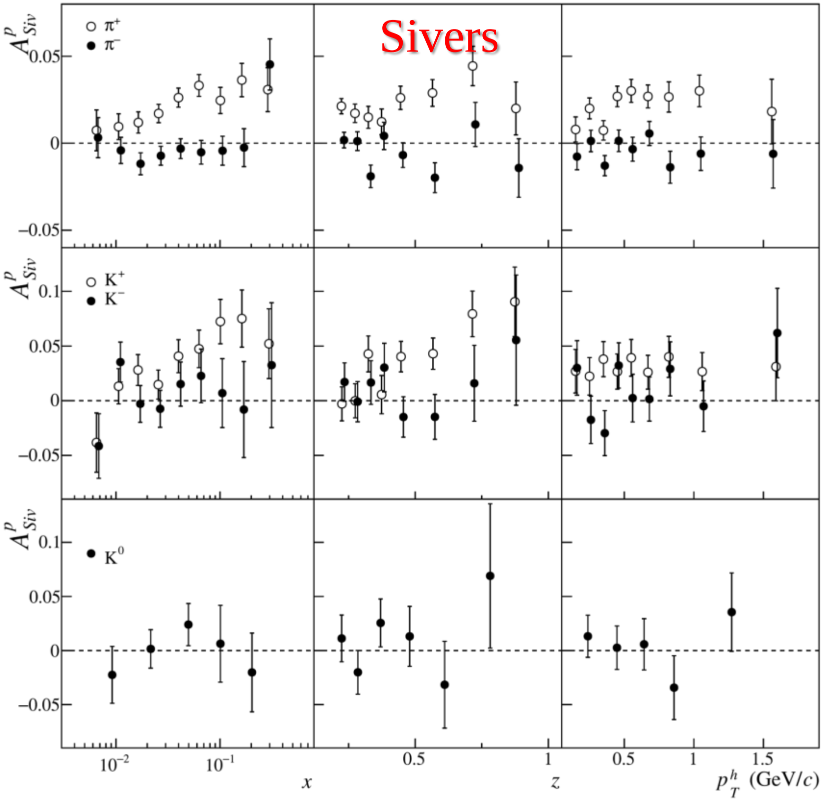
$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T}+\varepsilon F_{UU,L}\right)\left\{1+\ldots+S_{\mathrm{T}}\, A_{UT}^{\sin(\phi_h-\phi_S)}\sin\left(\phi_h-\phi_S\right)+S_{\mathrm{T}}\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin\left(\phi_h+\phi_S\right)\ldots\right\}$$

$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)}=C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h}h_1^q H_{1q}^{\perp h}\right]}$$

$$\boxed{F_{UT,T}^{\sin(\phi_h-\phi_S)}=C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{k_T}}{M}f_{1T}^{\perp q}D_{1q}^h\right],F_{UT,L}^{\sin(\phi_h-\phi_S)}=0}$$

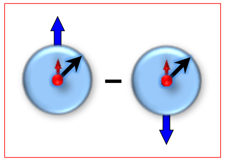
COMPASS PLB 744(2015)250





- 1st COMPASS deuteron measurements – Collins and Sivers asymmetries compatible with zero
- COMPASS proton measurements – clear non-zero signal for both asymmetries

SIDIS TSAs: Collins effect and Transversity

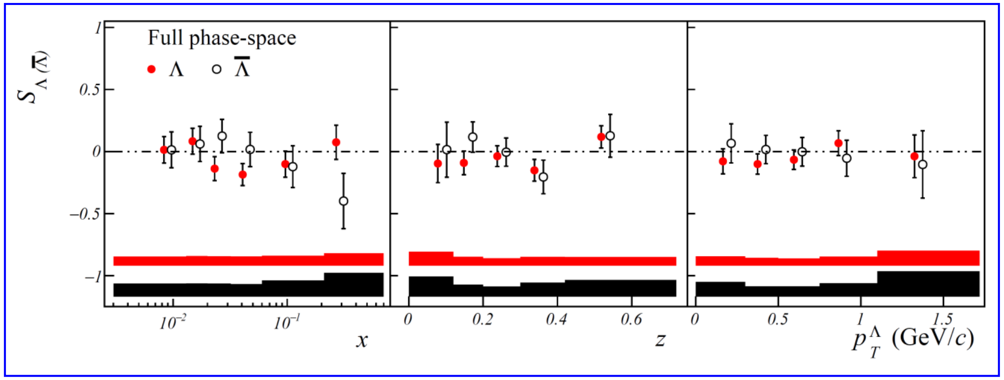


$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right)\left\{1 + \ldots + S_T\, \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h + \phi_S) + \ldots\right\}$$

$$\boxed{F_{UT}^{\sin(\phi_h+\phi_S)} = C\left[-\frac{\hat{\boldsymbol{h}}\cdot \boldsymbol{p_T}}{M_h} h_1^q H_{1q}^{\perp h}\right]}$$

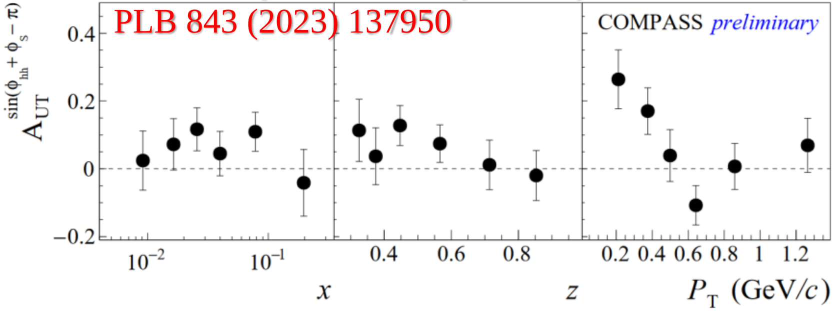
- Measured on P/D in SIDIS and in dihadron SIDIS
- Compatible results COMPASS/HERMES (Q^2 is different by a factor of ~2-3)
- No impact from Q^2-evolution?

PLB 824 (2022) 136834

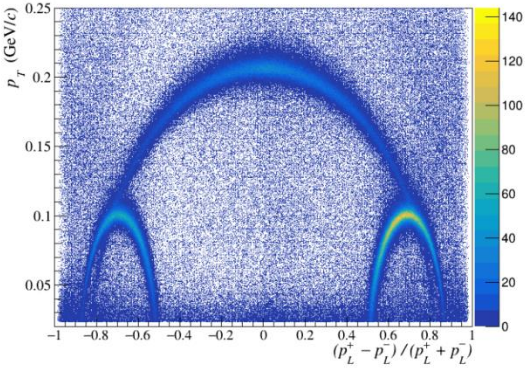


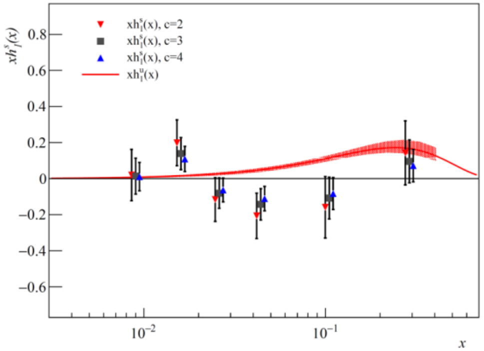
Inclusive ρ^0 Collins asymmetry

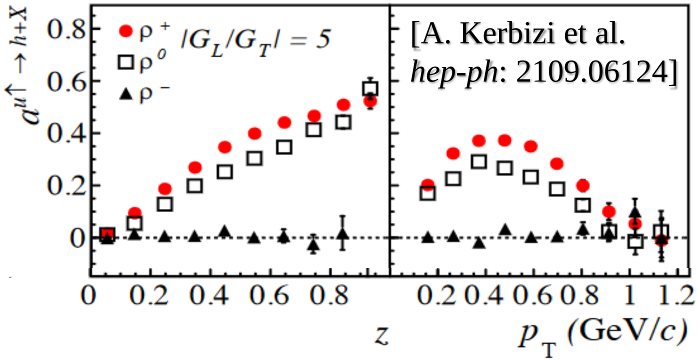
PLB 843 (2023) 137950



- indication for a positive asymmetry
- opposite to π^+ and π^0 as predicted by the models
- Large effect at small P_T







[A. Kerbizi et al. *hep-ph*: 2109.06124]